SLIDES-24-0291-PPD-V

Latest Neutrino Oscillation Results from the NOvA Experiment

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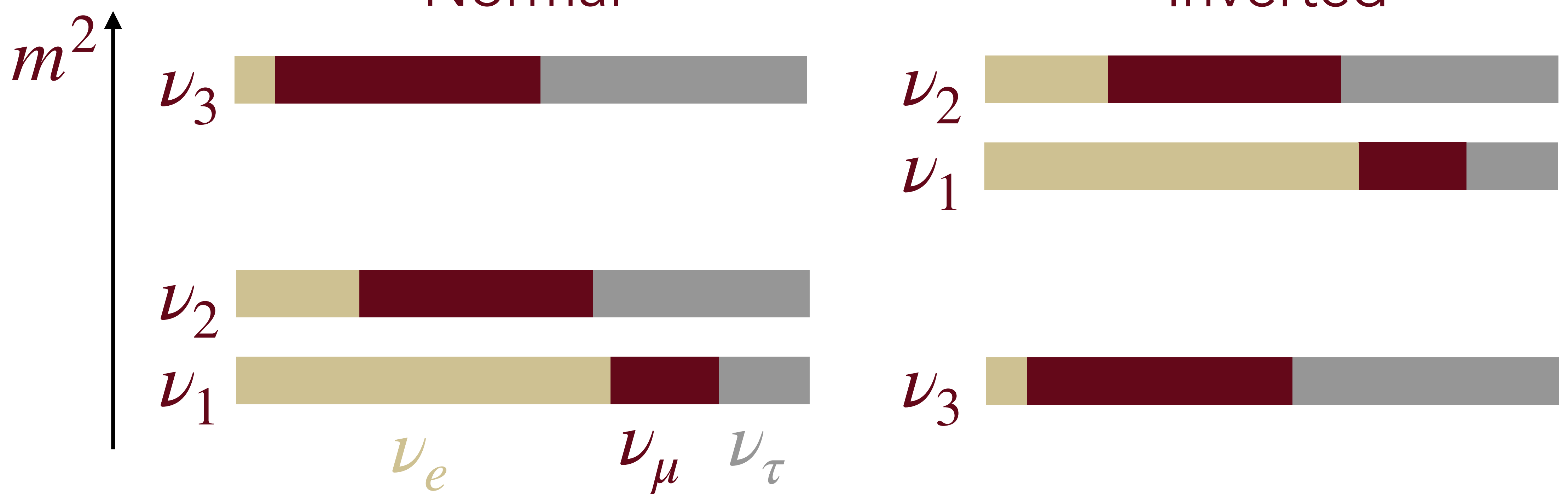
Neutrino oscillations in NOvA

3-flavor Oscillations

Mass Ordering

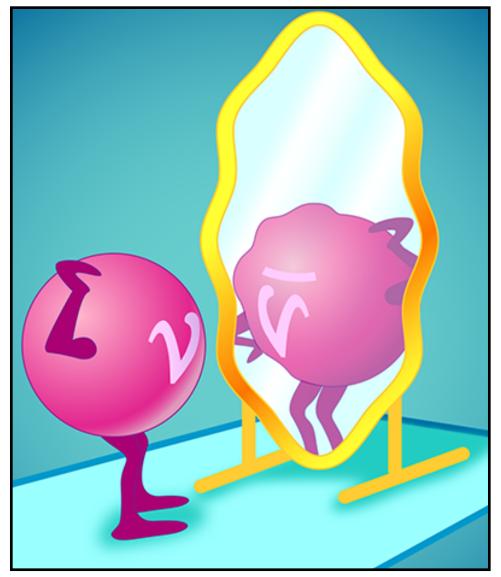
Is ν_3 the heaviest state?

Normal | Inverted



CP Violation

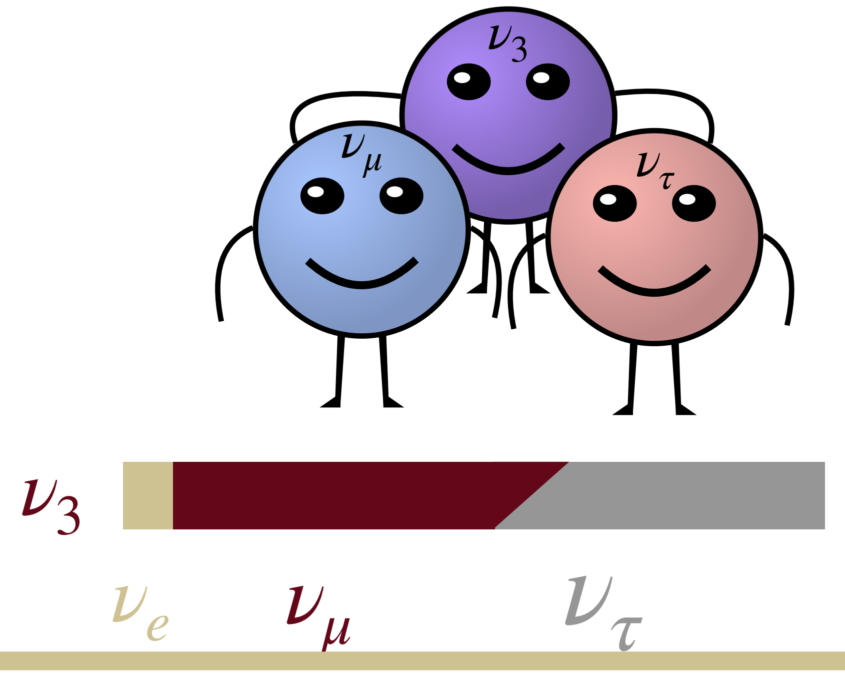
Is there a neutrino-antineutrino asymmetry?



Credit: APS/Carin Cain

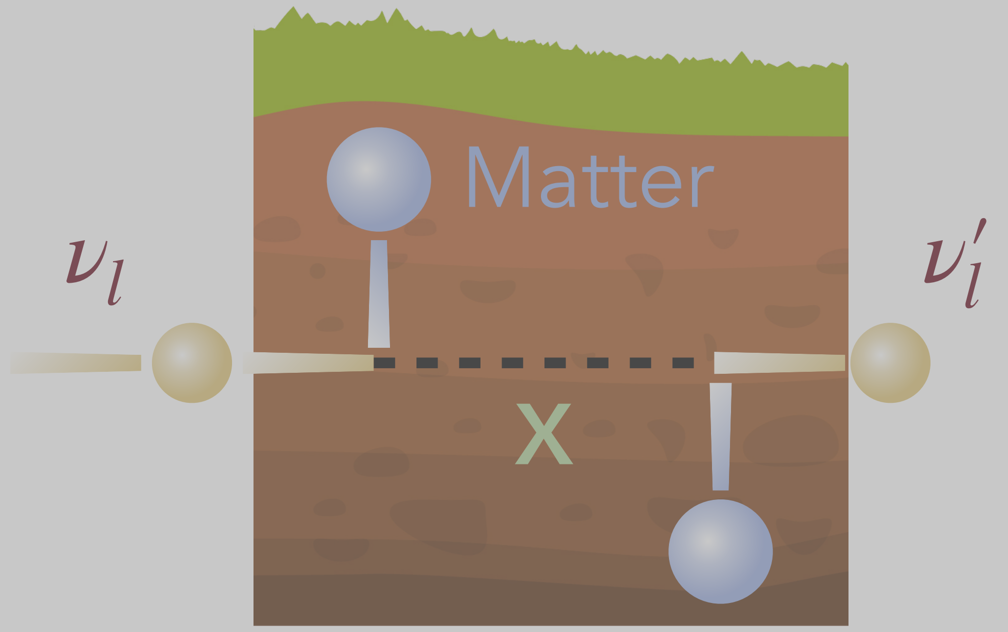
Maximal Mixing (θ_{23})

Do the ν_μ and ν_τ states couple equally to ν_3?

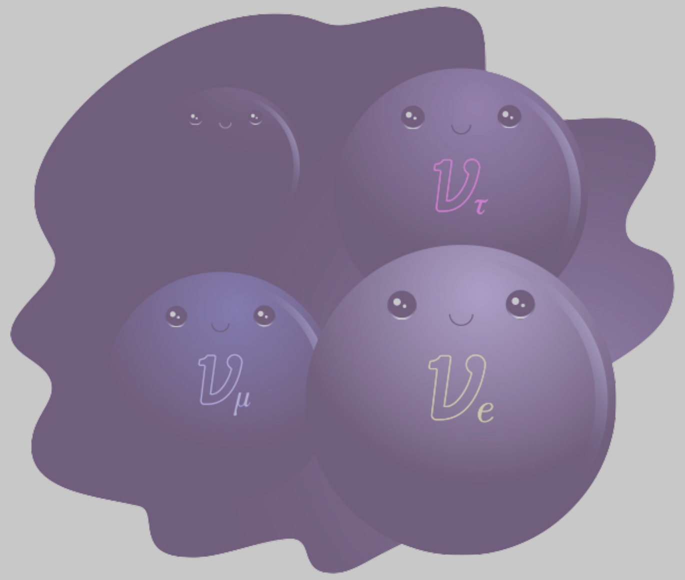


Beyond Standard Oscillations

Nonstandard interactions

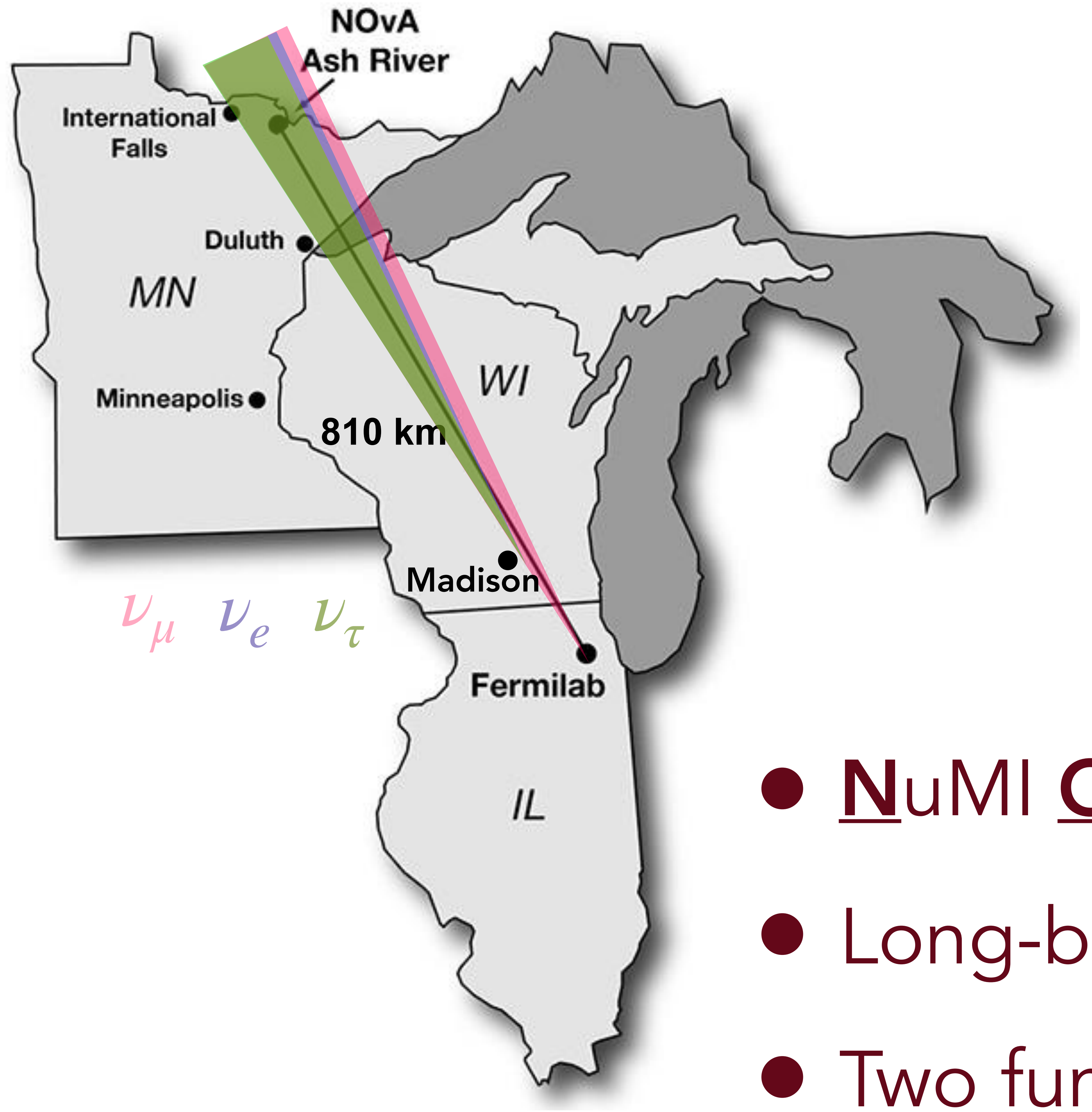


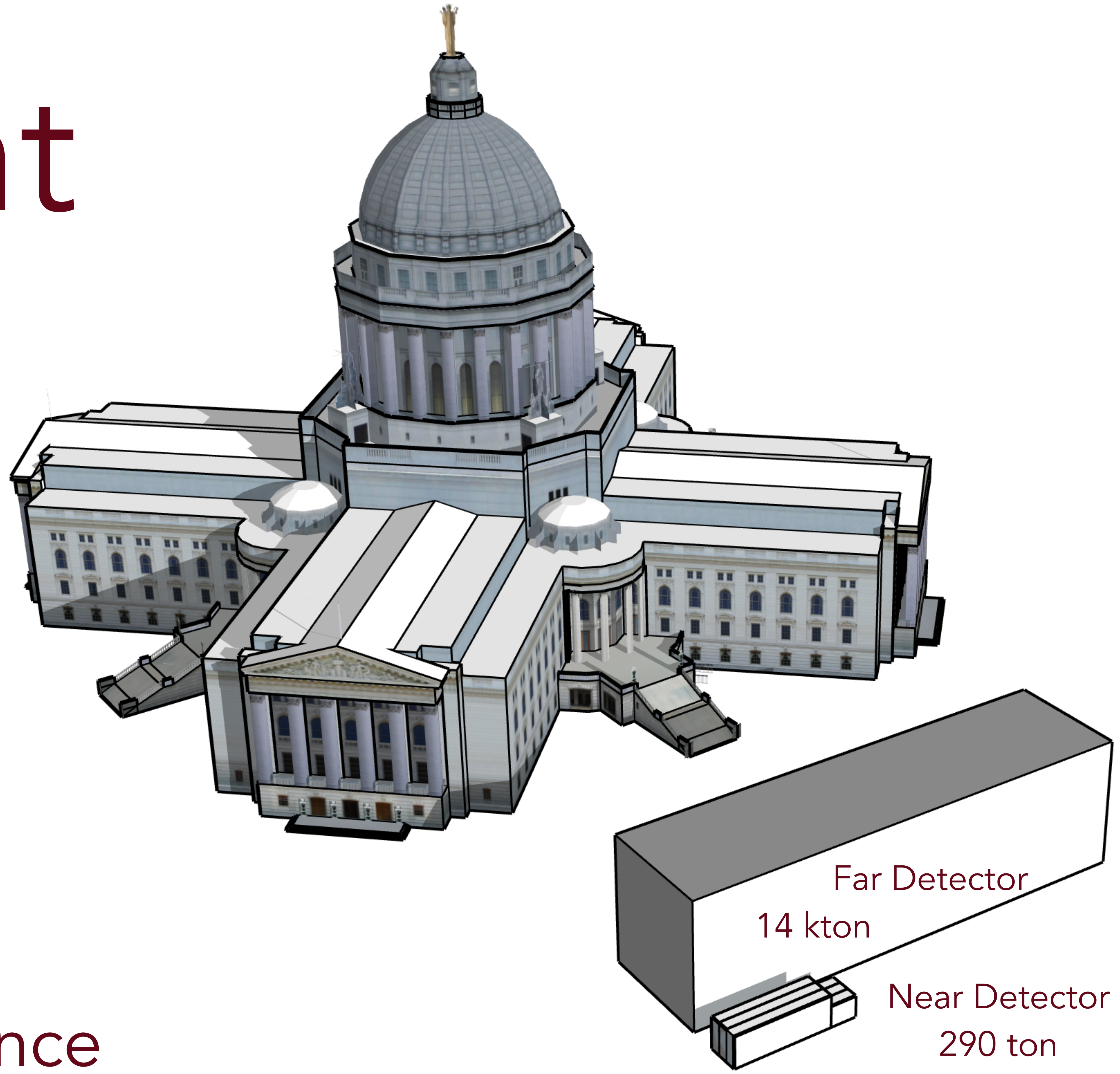
Sterile neutrinos



Credit: Symmetry magazine, Illustration by Sandbox Studio, Chicago with Ana Kova

The NOvA experiment

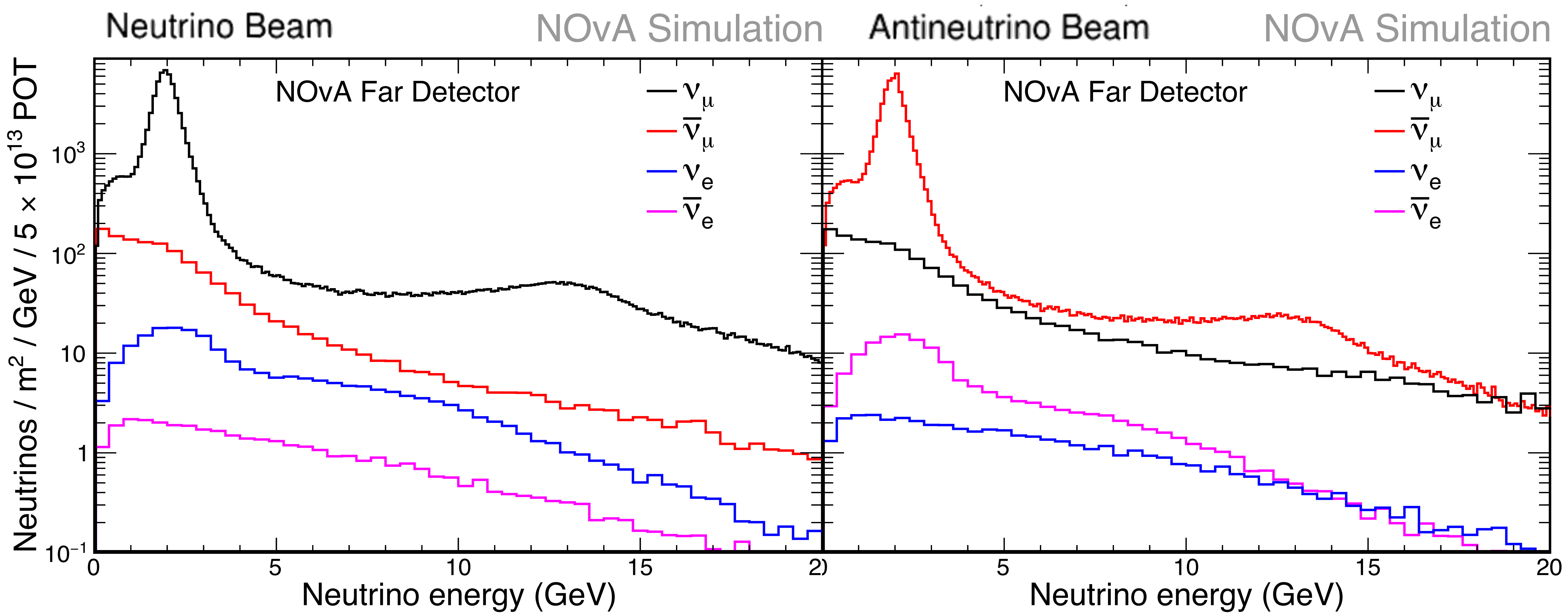


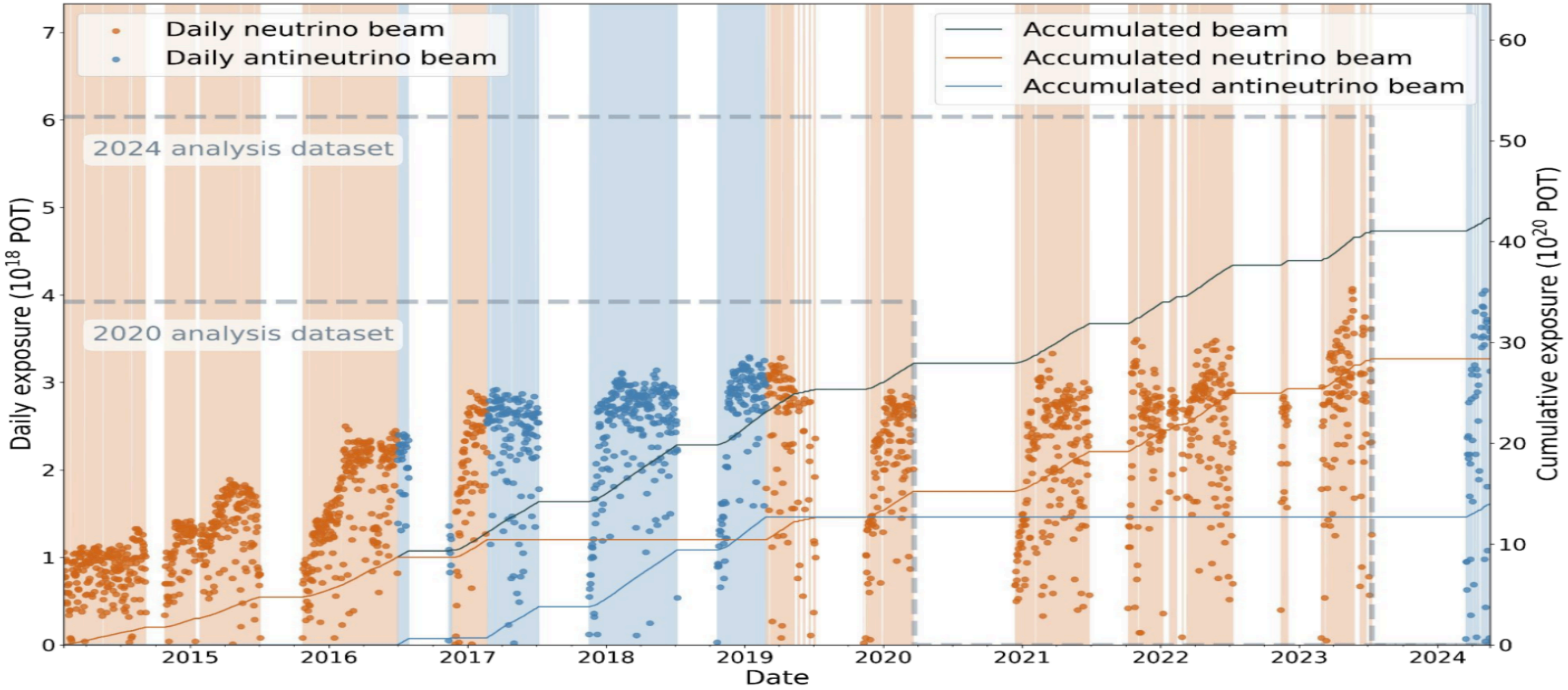


- **N**uMI **O**ff-Axis ν_e **A**ppearance
- Long-baseline accelerator neutrino experiment based at Fermilab
- Two functionally equivalent tracking calorimeters in a narrow-band 2 GeV ν_μ or $\bar{\nu}_\mu$ beam

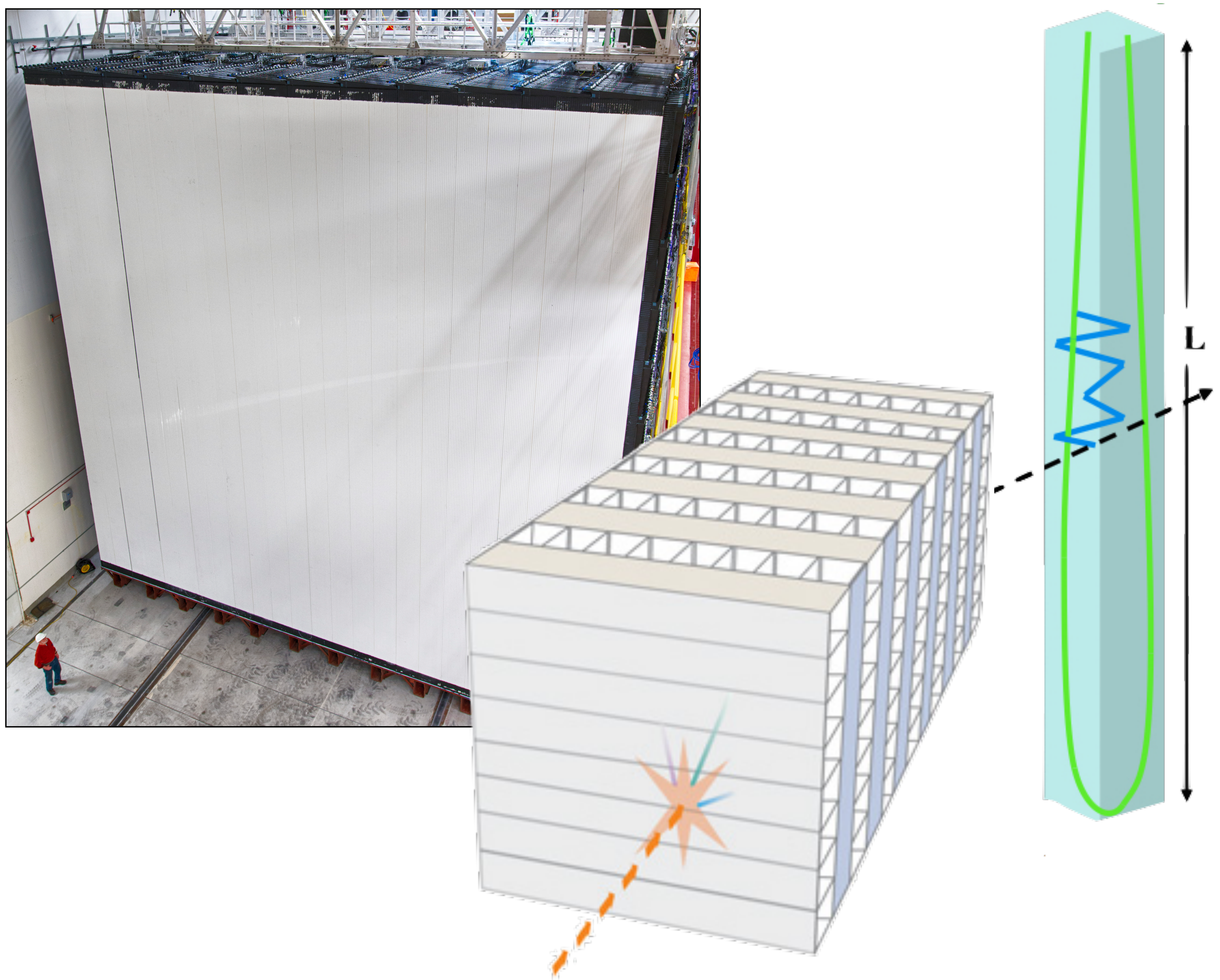
The NuMI beam

- 39.1×10^{20} analyzed POT so far
  - 10 years of running
- Typical beam power of ~900 kW
  - Record powers above 1 MW
- Selectable ν_μ or $\bar{\nu}_\mu$ beam
  - 93-95% purity

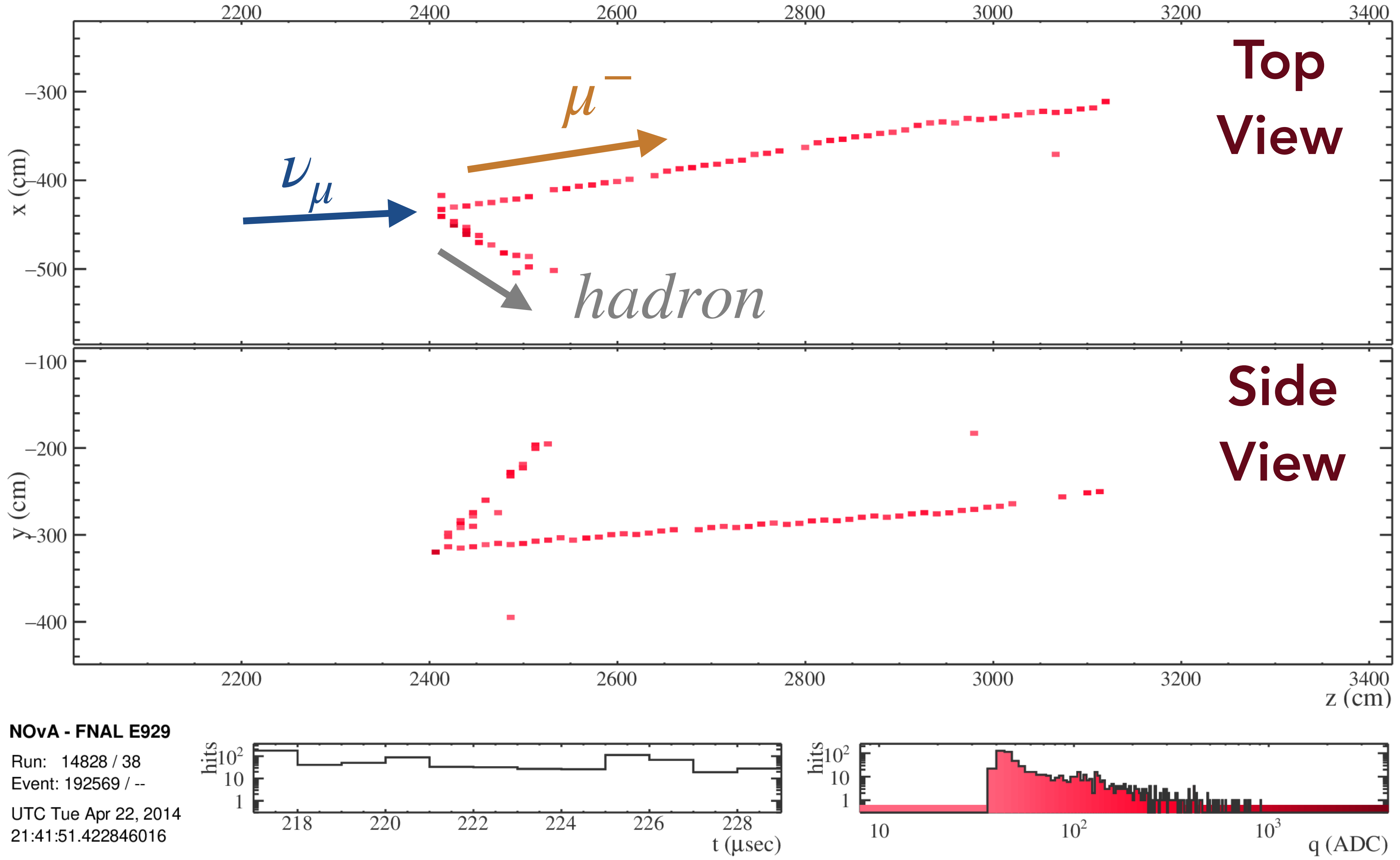




The NOvA detectors

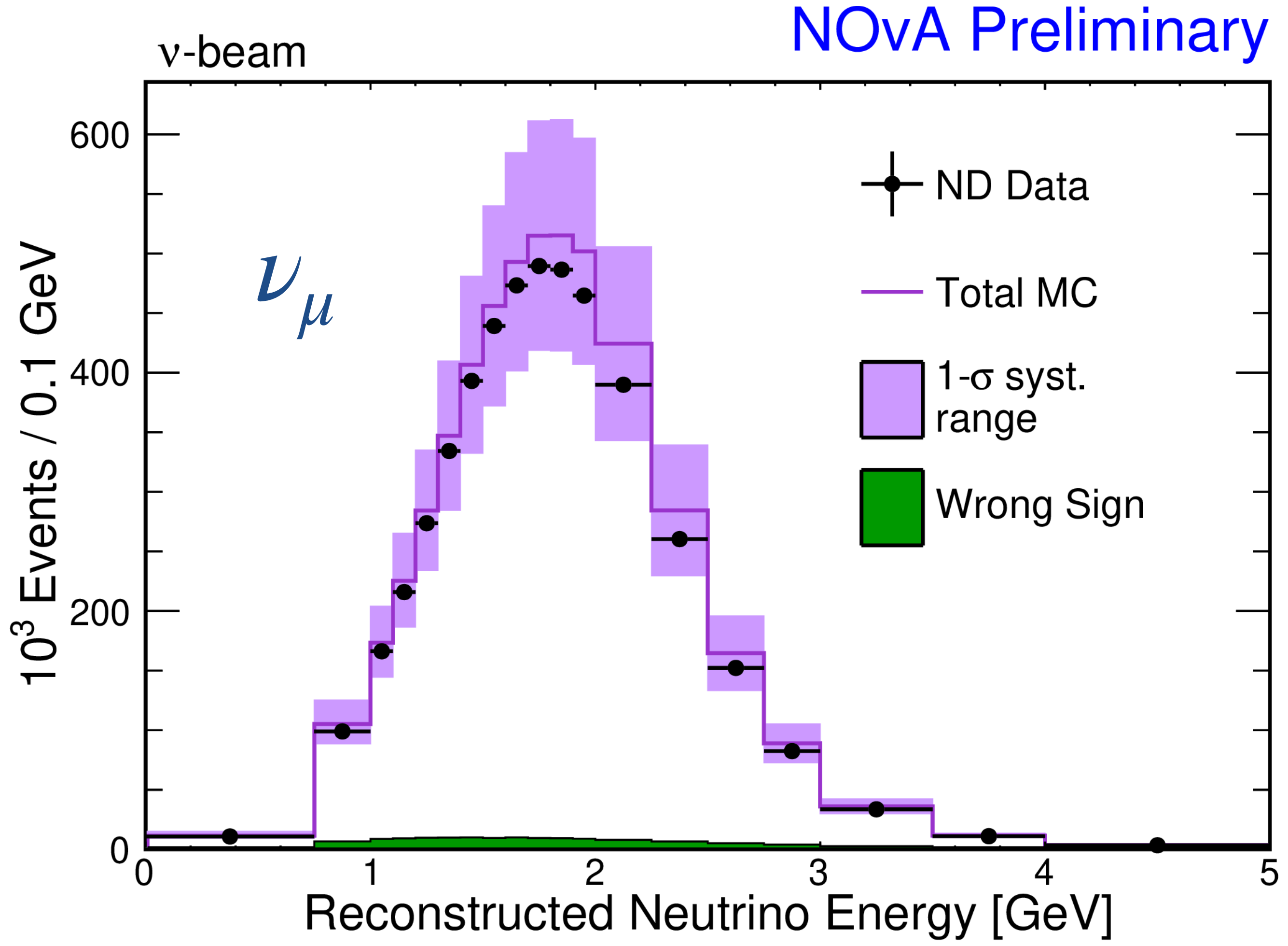


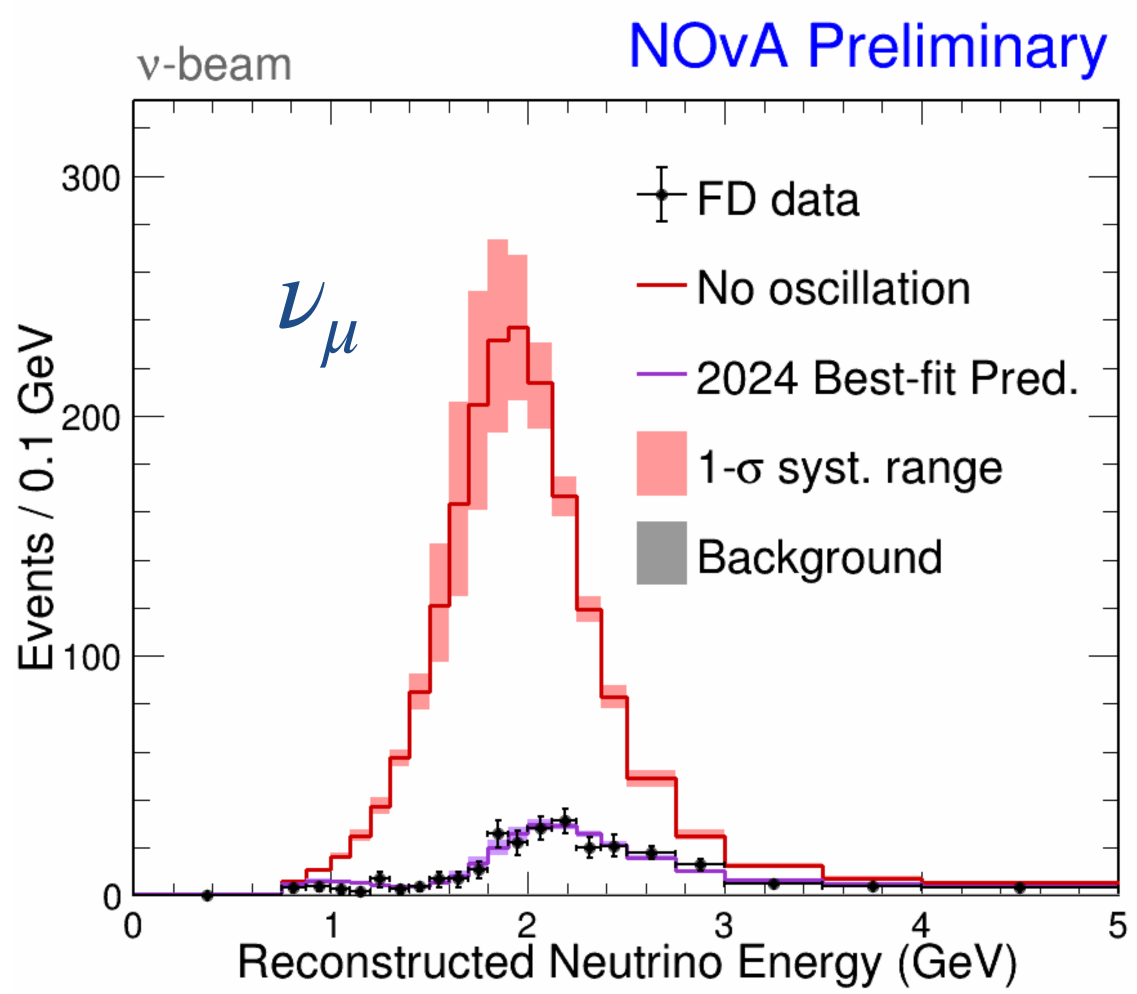
- Extruded PVC cells filled with scintillating oil
- Looped wavelength shifting fiber viewed by an avalanche photodiode
- Alternating horizontal and vertical planes for 3D reconstruction



How we measure 3-flavor oscillations

- ND and FD are functionally identical
  - They share many systematic uncertainties (neutrino cross sections and beam flux)
- Use ND data to correct the ND simulation
  - Extrapolate corrected ND simulation to generate data-corrected FD predictions
  - Repeat for different combinations of oscillation parameters and fit

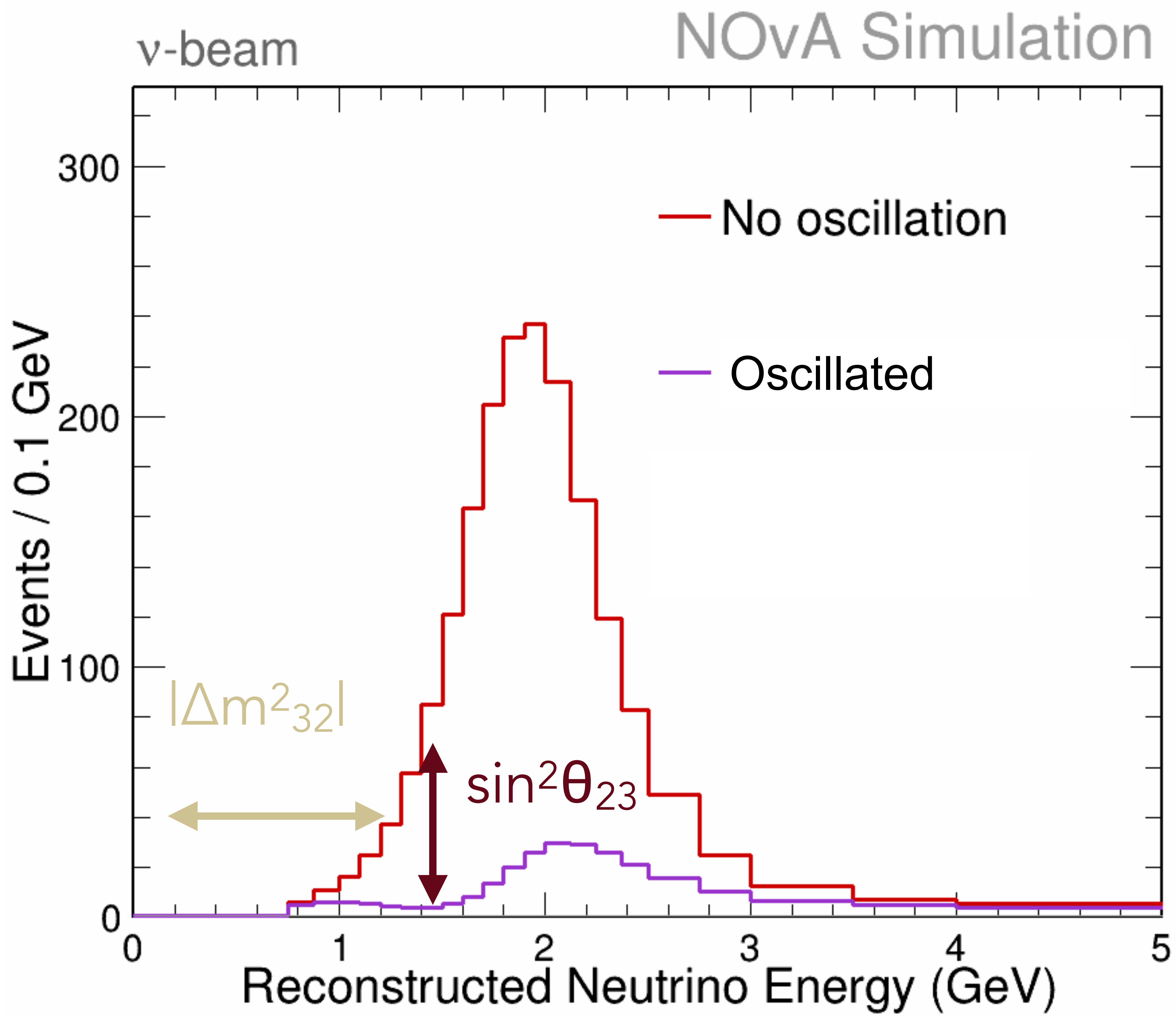




Decoding our measurements

$\overset{(-)}{\nu}_\mu$ survival

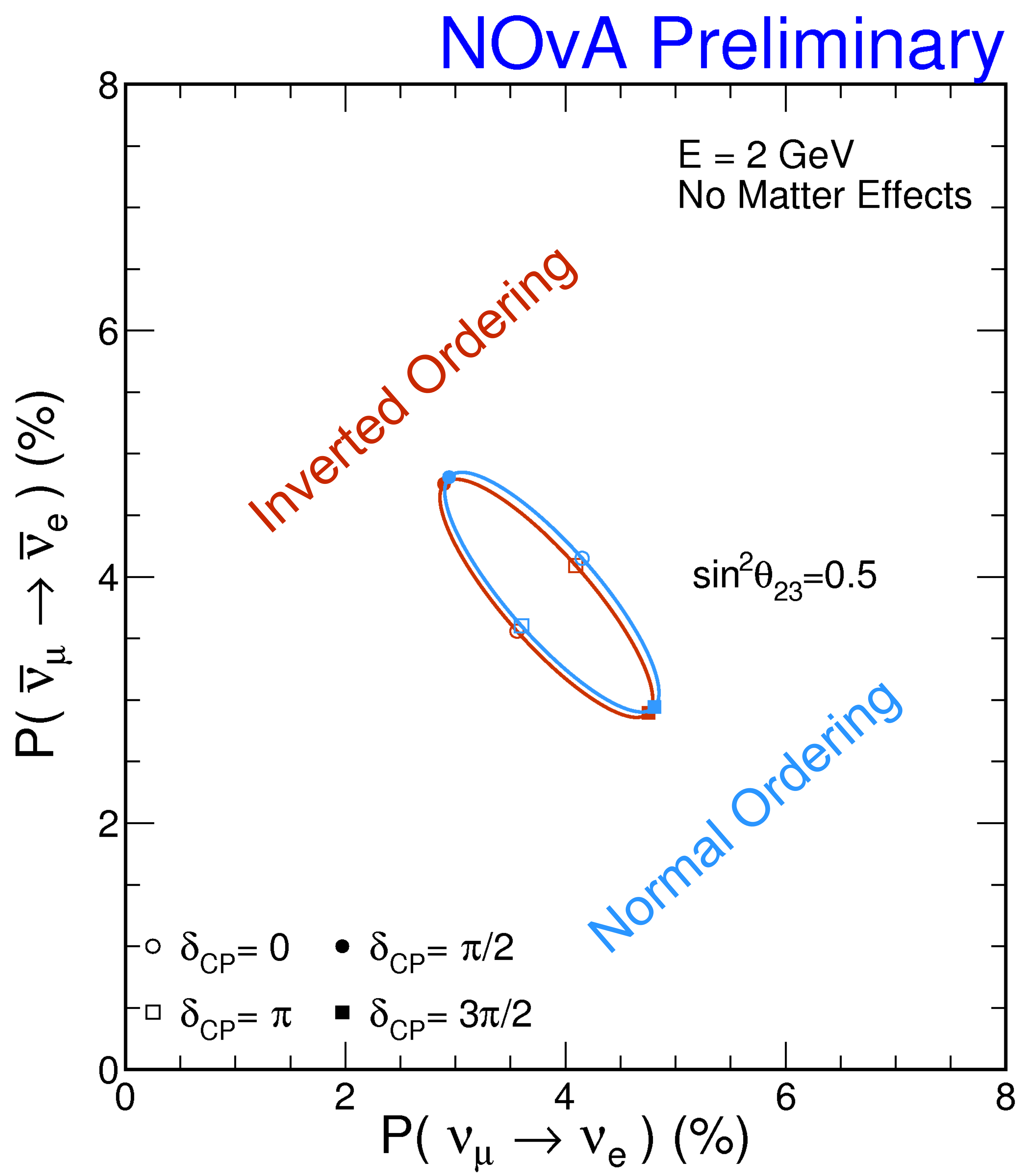
- Dip location depends on Δm^2_{32}
- Dip amplitude depends on θ_{23}



Decoding our measurements

$\overset{(-)}{\nu}_e$ appearance

- Compare neutrino and antineutrino oscillations
- Produces ellipses based on δ_{CP} and mass ordering
- With maximal mixing and vacuum oscillations the mass ordering and δ_{CP} choices create degeneracies

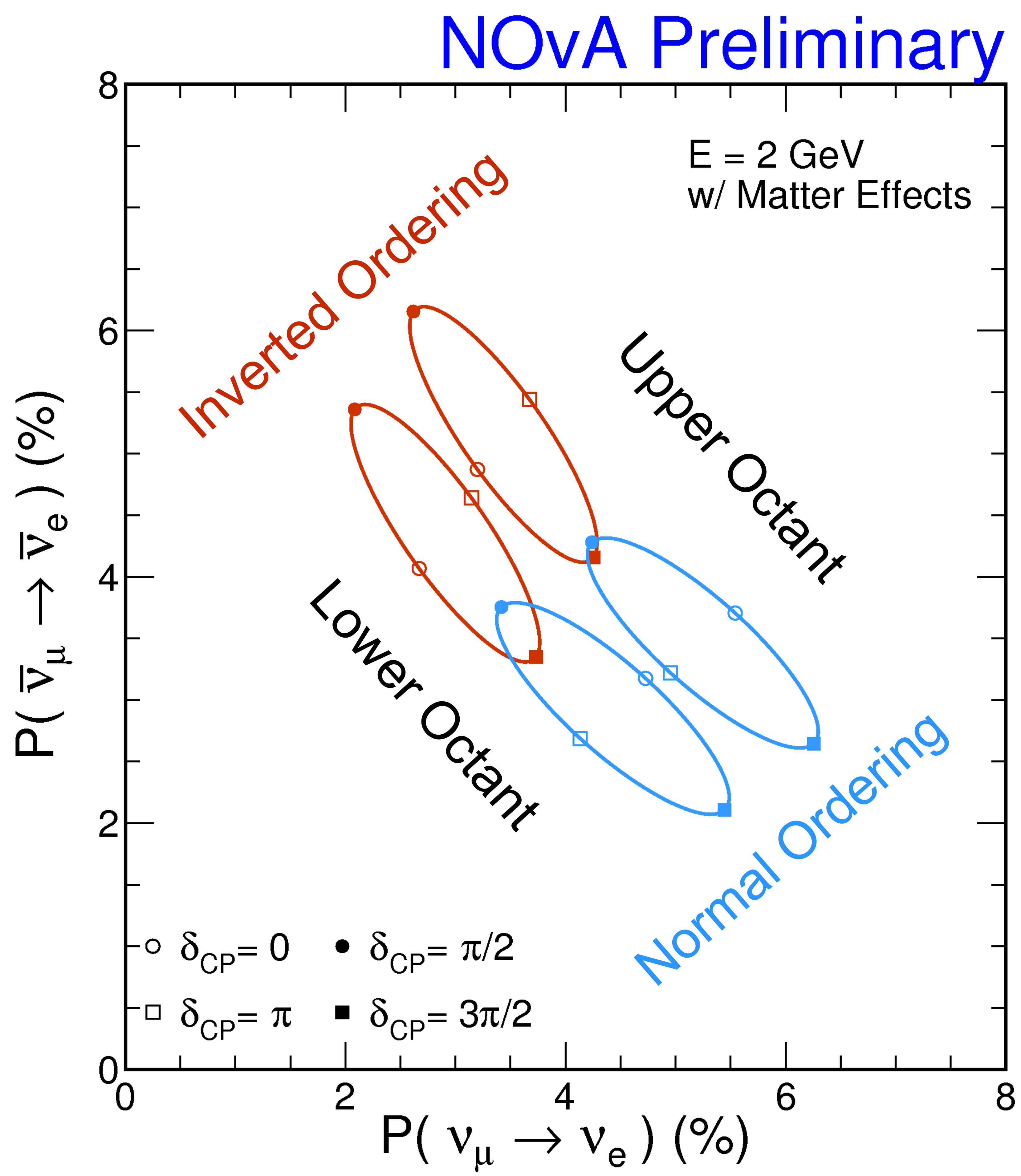


Decoding our measurements

$\overset{(-)}{\nu}_e$ appearance

- Matter effects and θ_{23} octant pulls the ellipses apart further splits the ellipses

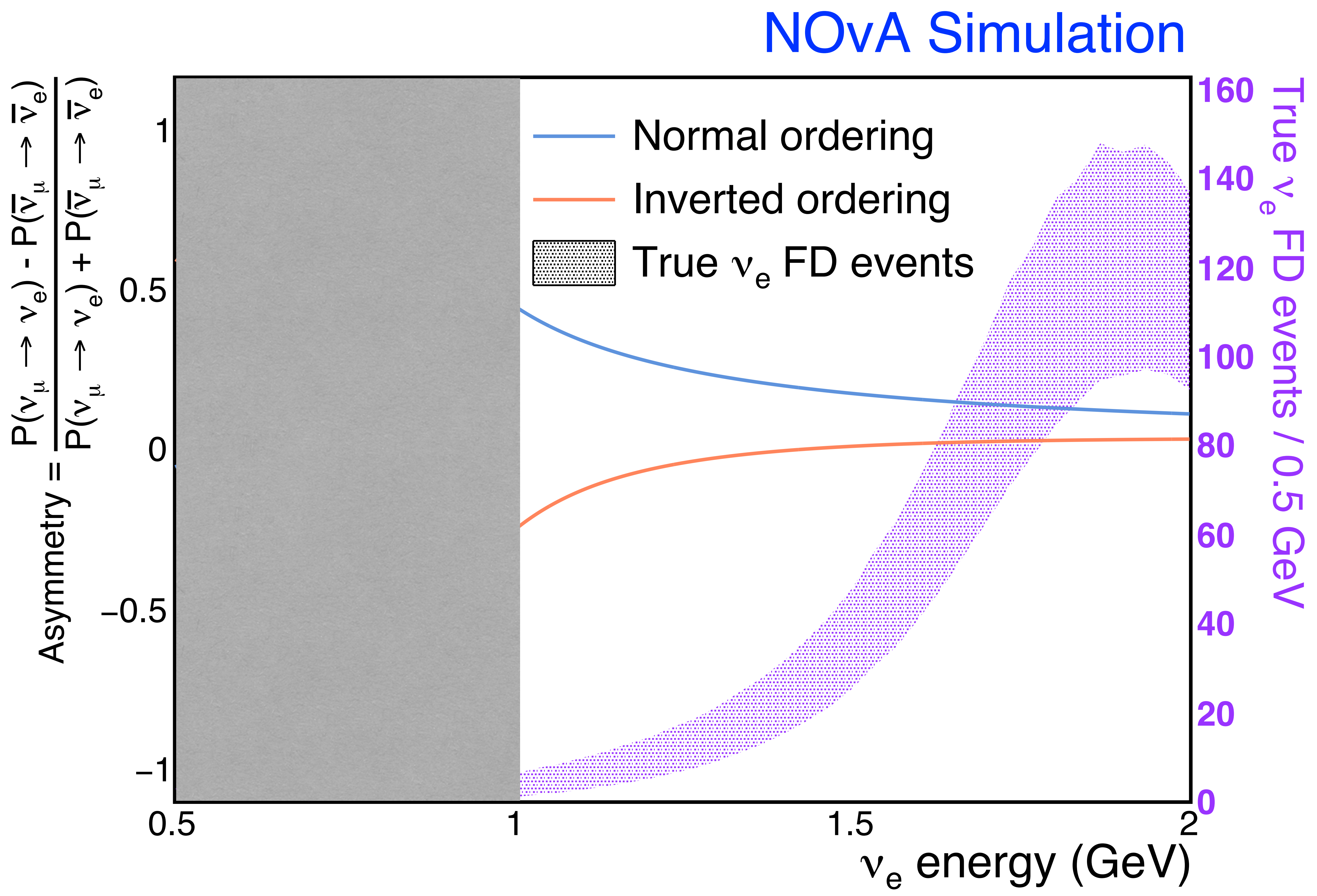
- There are still degenerate regions near the middle



Latest analysis additions

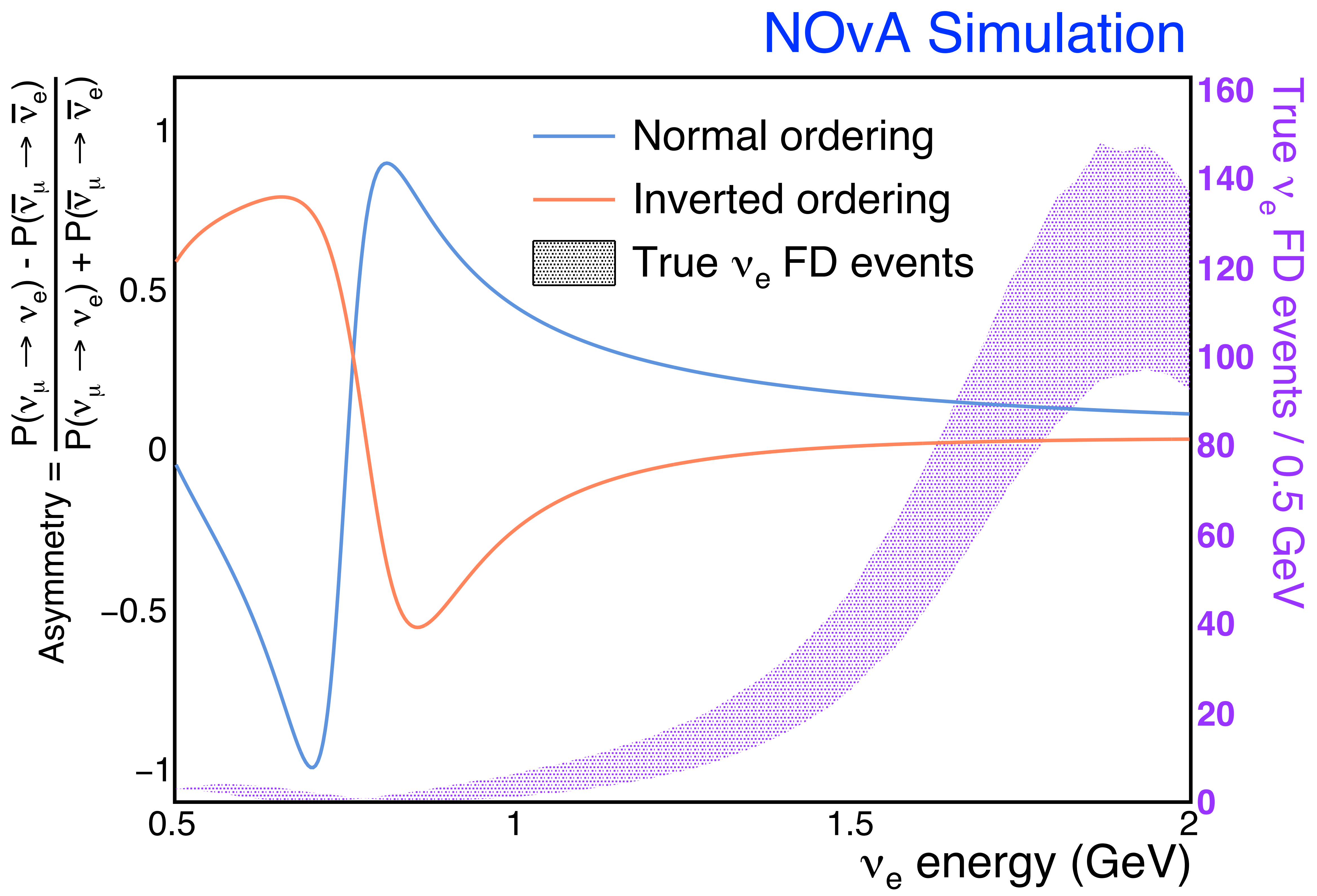
Low energy ν_e

- Previous analyses were restricted to E > 1 GeV
- ν_e samples act more like a counting experiment



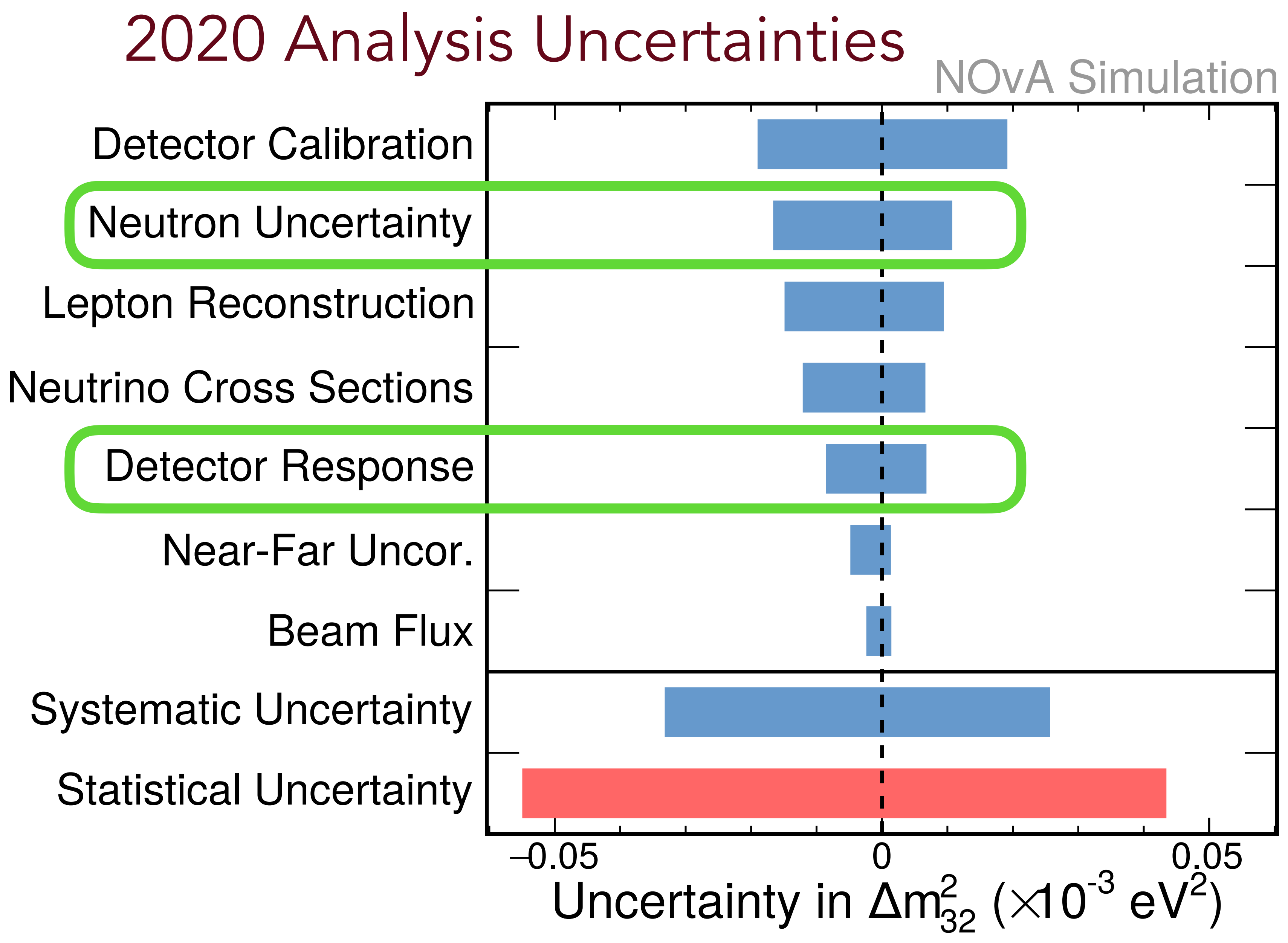
Low energy ν_e

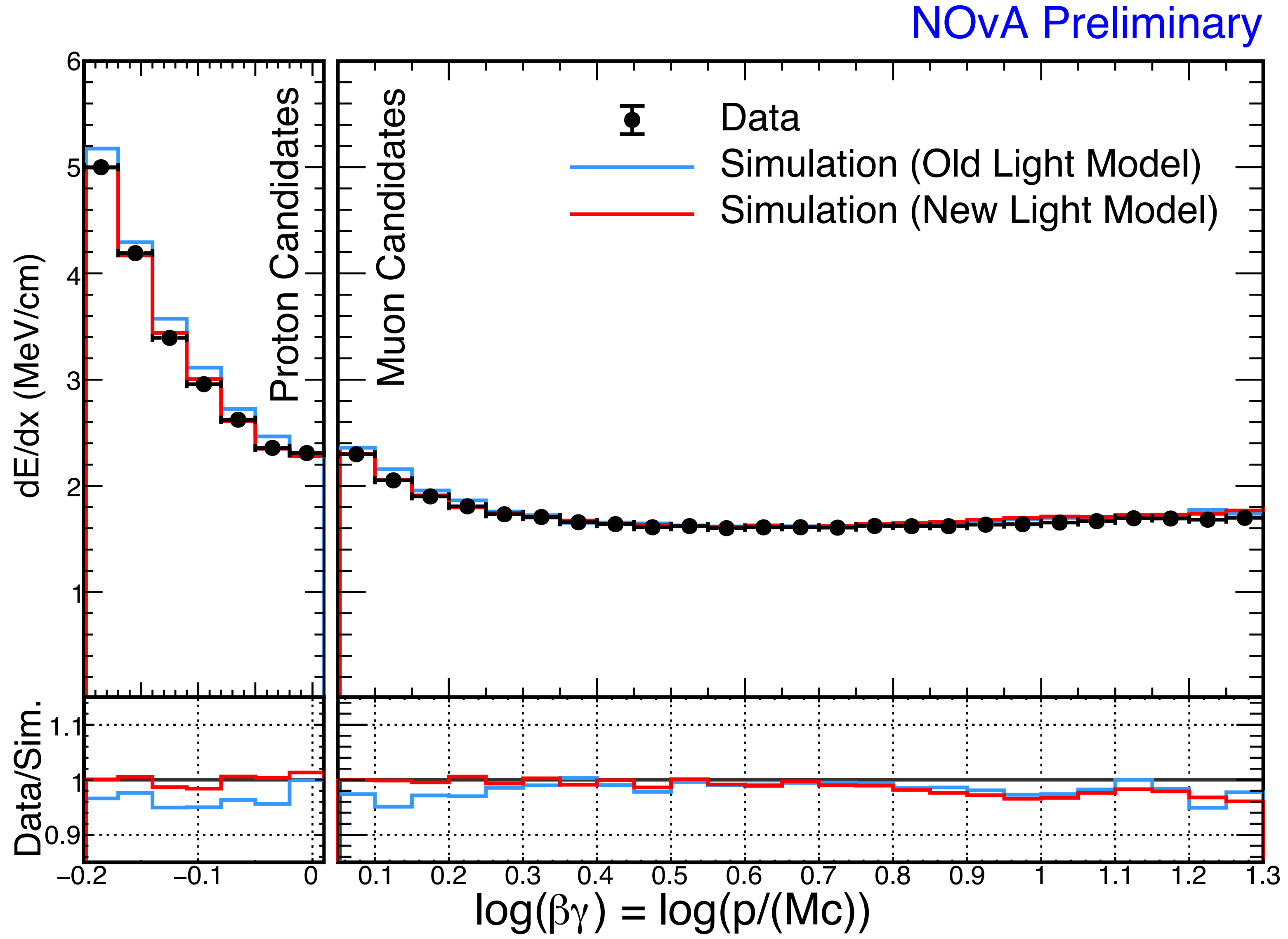
- Previous analyses were restricted to E > 1 GeV
- ν_e samples act more like a counting experiment
- More shape info available at lower energies
  - Improves mass ordering sensitivity by a few percent
  - But low statistics
    - No low energy events for antineutrino beam

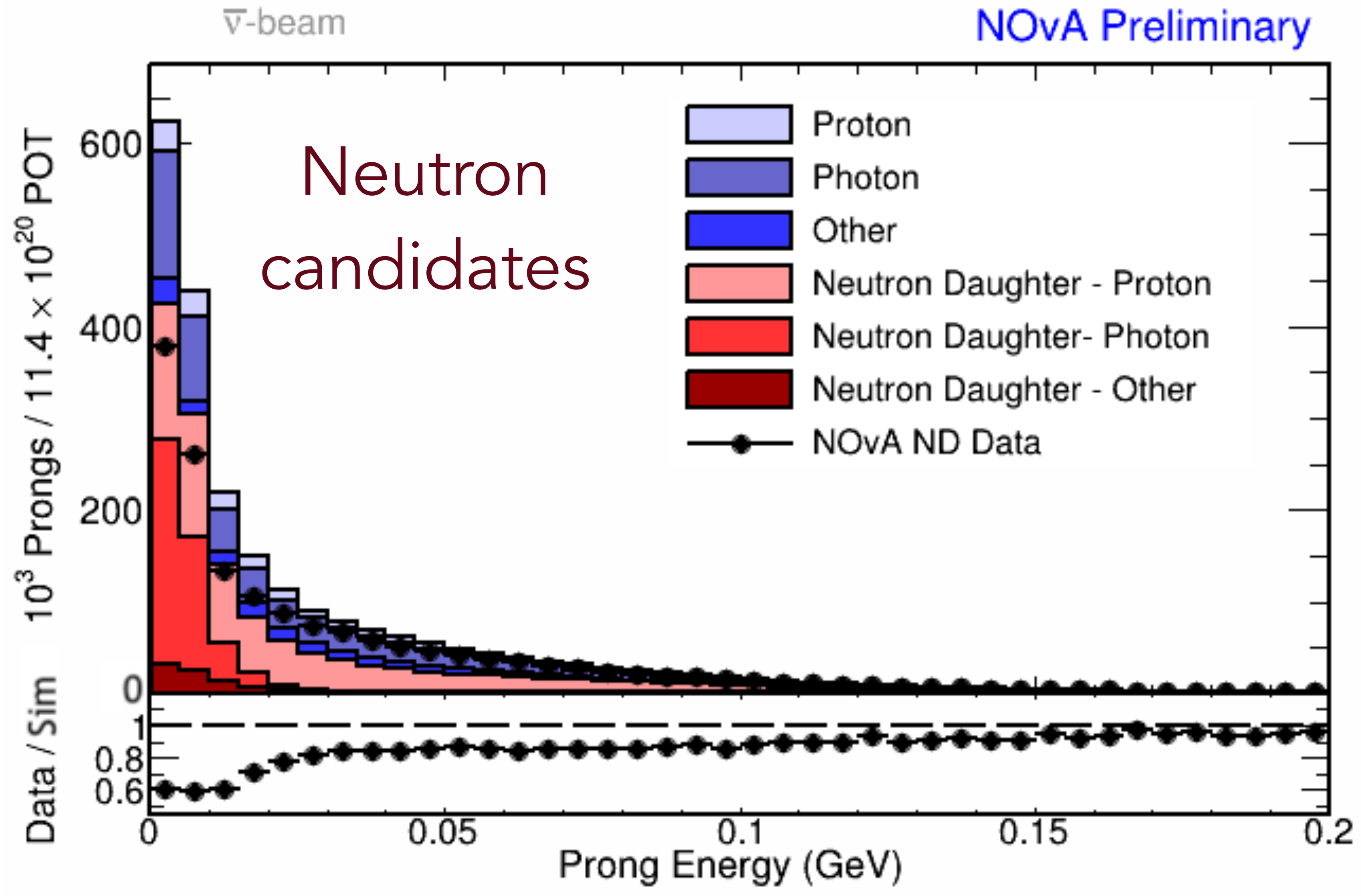


Detector modeling

- Imperfections in the models for neutron interactions and light production have been leading uncertainties
- New light tuning agrees much better with data
  - Combined fit to multiple ND samples
- Observed an over-simulation of neutron candidates

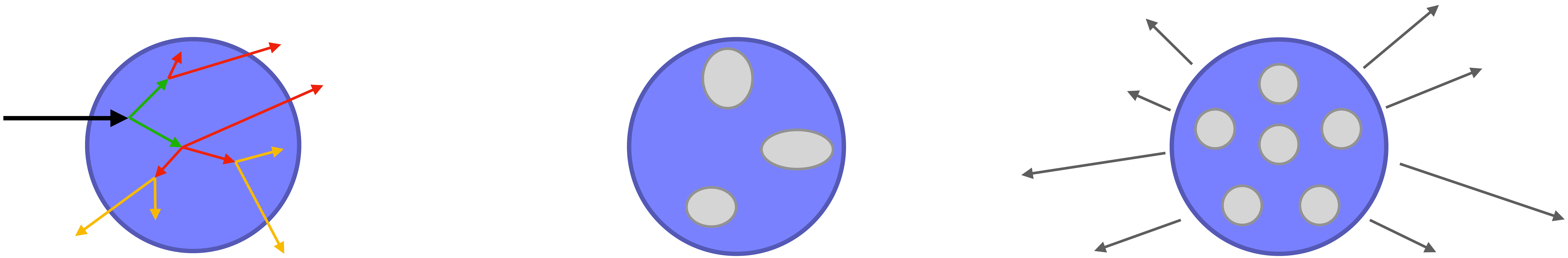






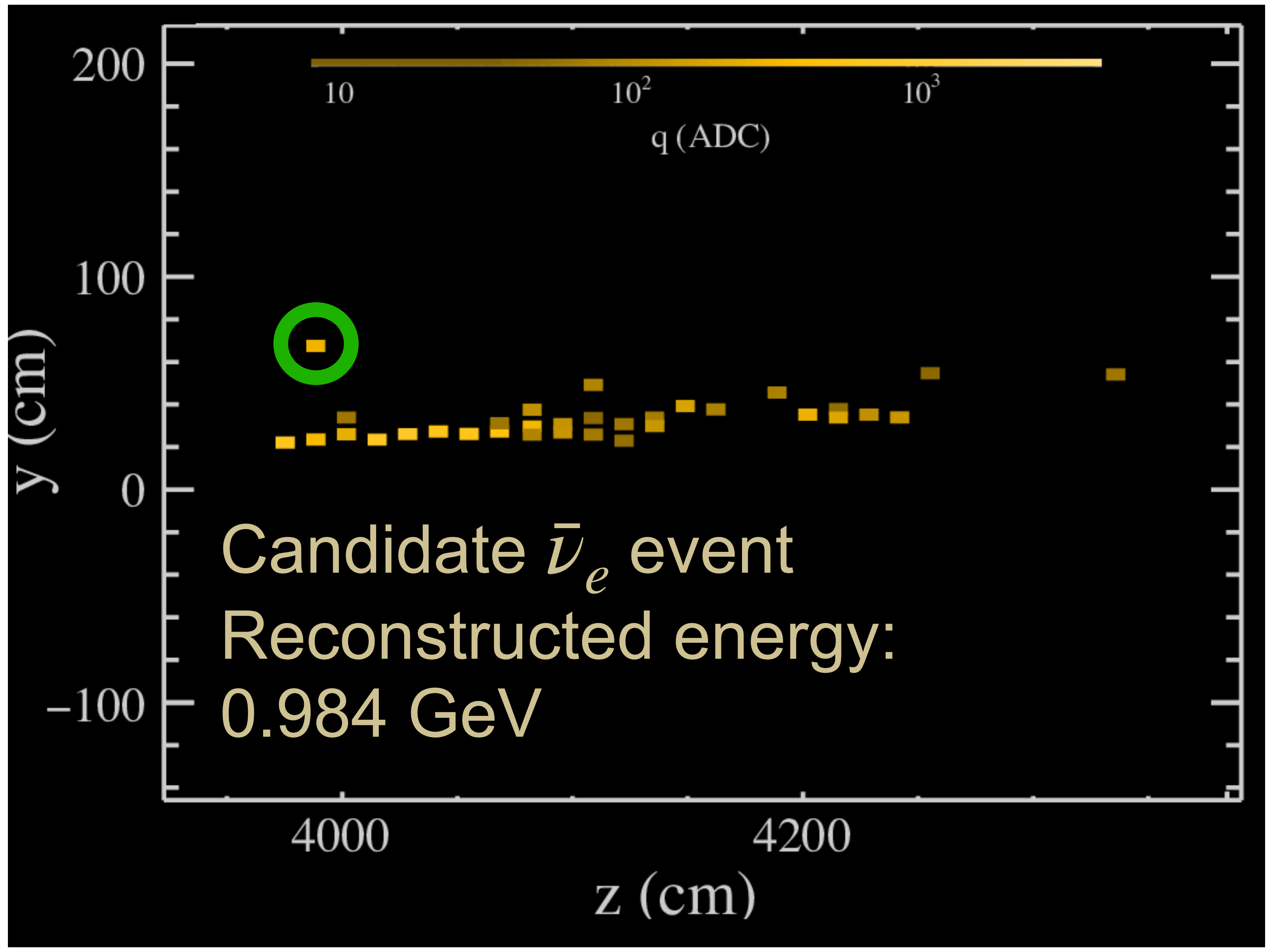
The problem with neutrons

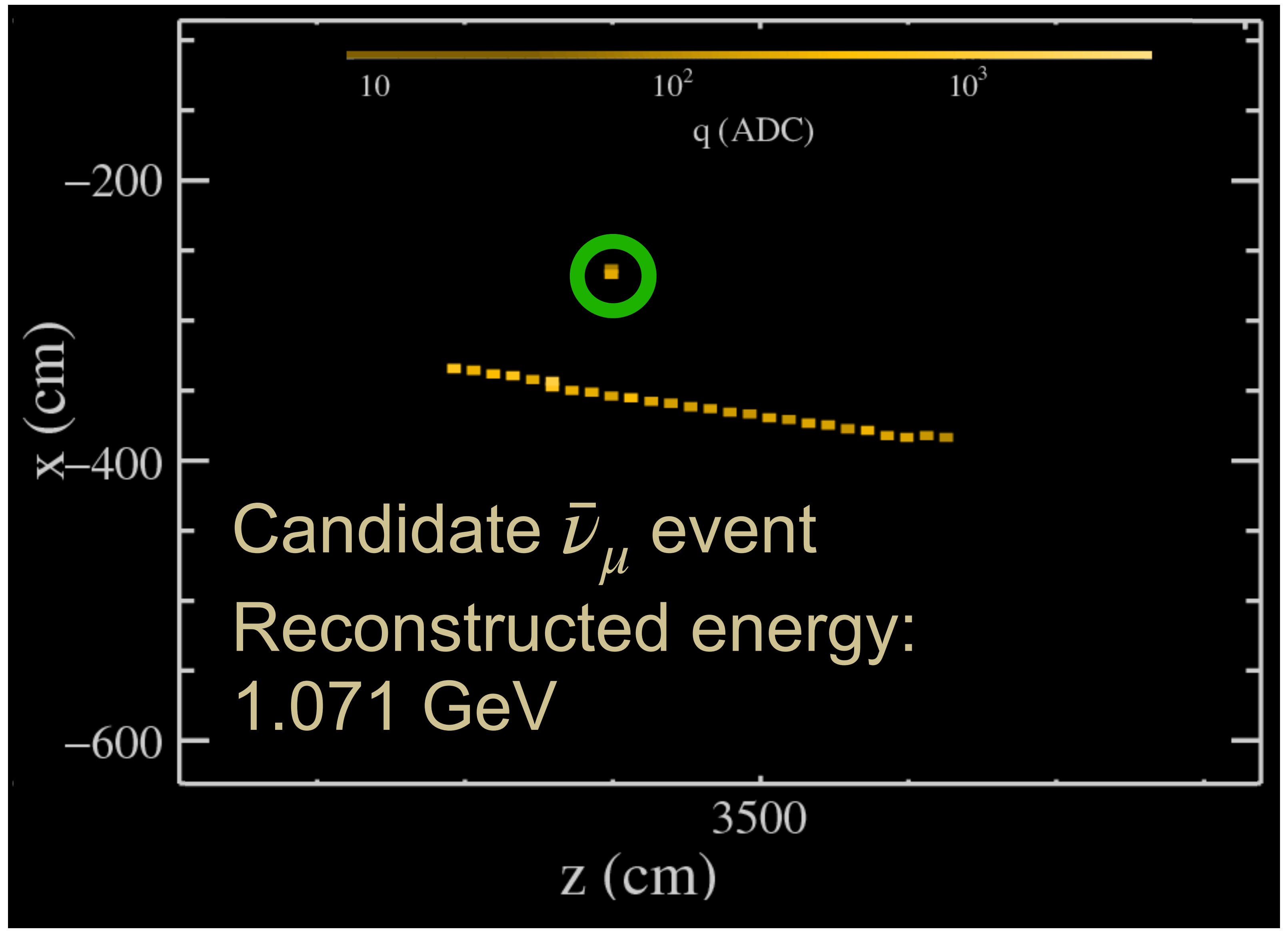
- To study neutrinos we need to know their incoming energy
- Neutrinos are neutral → invisible until they interact → sum energy of outgoing particles
- Neutrons are neutral → can carry energy away unseen
- Our nuclear colleagues have done a great job with them, but generally at lower energies (from thermal to ~20 MeV)



Neutron selection

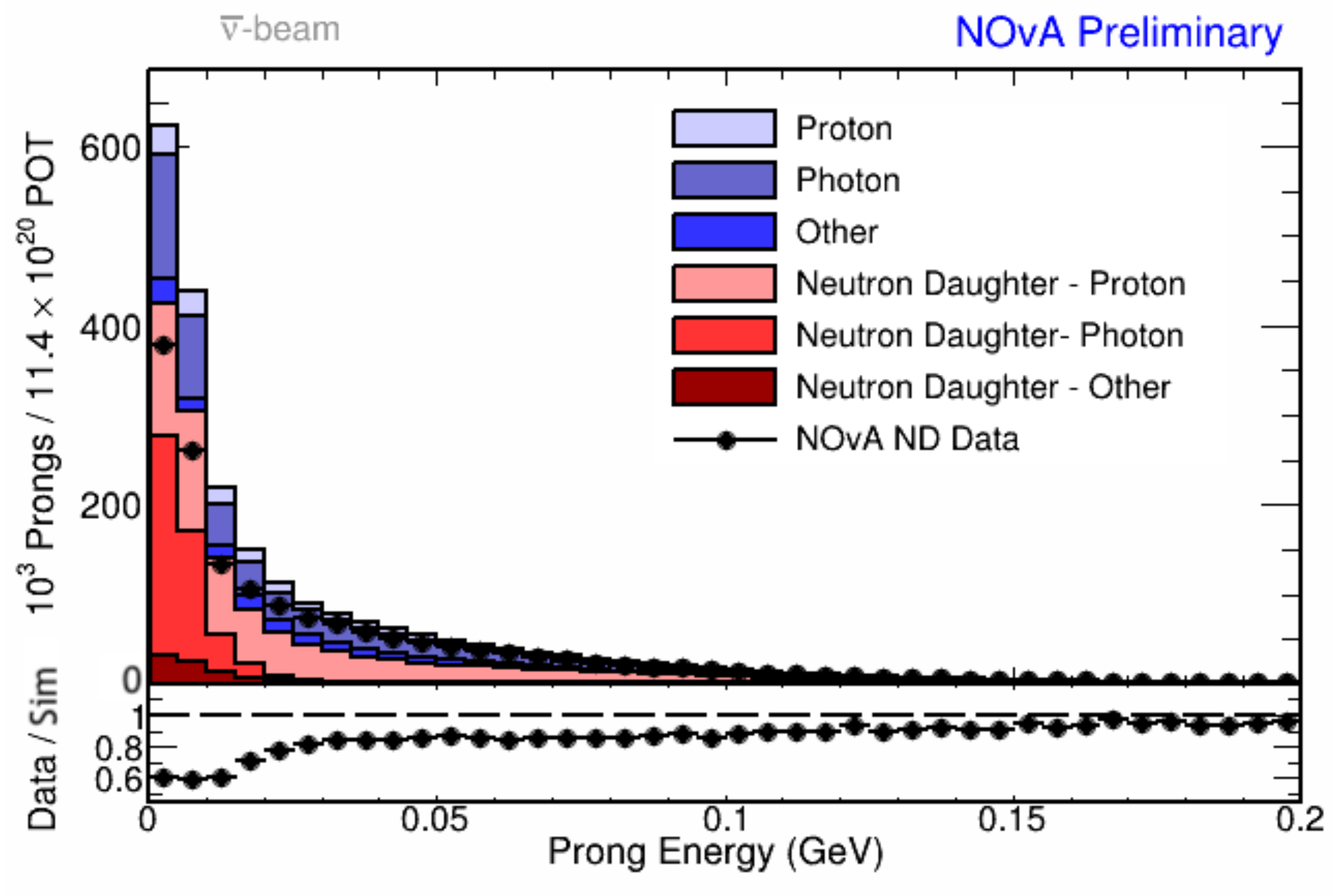
- Three main interaction modes
  - Elastic scattering: nuclear recoil energy is typically low
  - Inelastic scattering: produces photons and charged particles
  - Neutron capture: if they thermalize, on chlorine or hydrogen
- Developed a simple criteria to select neutron hit candidates
  - Many elastic scatters before producing visible particles
    - Hits should be > 20 cm from the neutrino interaction
    - A candidate should contain fewer than 6 hits
  - Selects visible neutrons with 71% efficiency and 61% purity

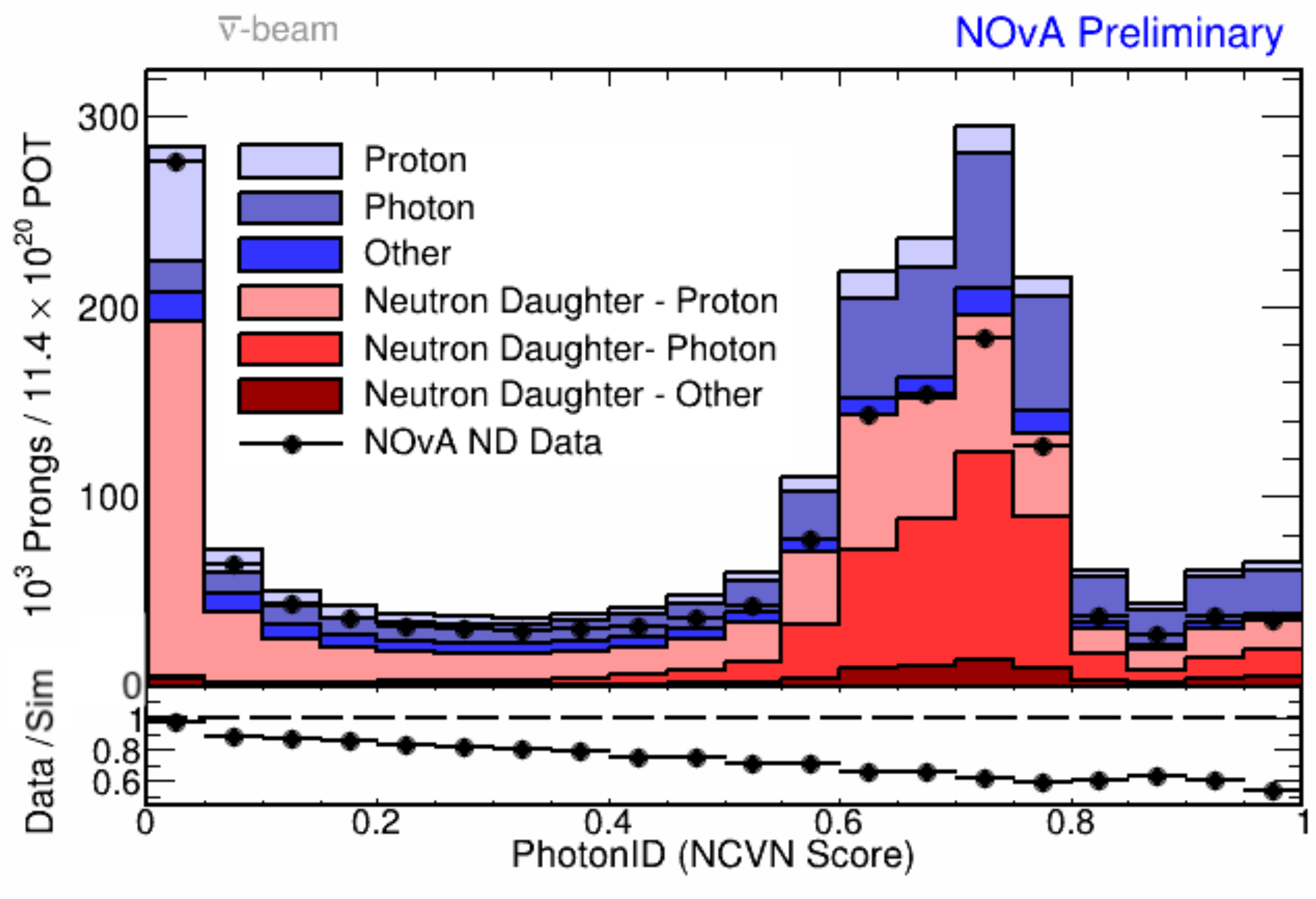




Neutron over-simulation

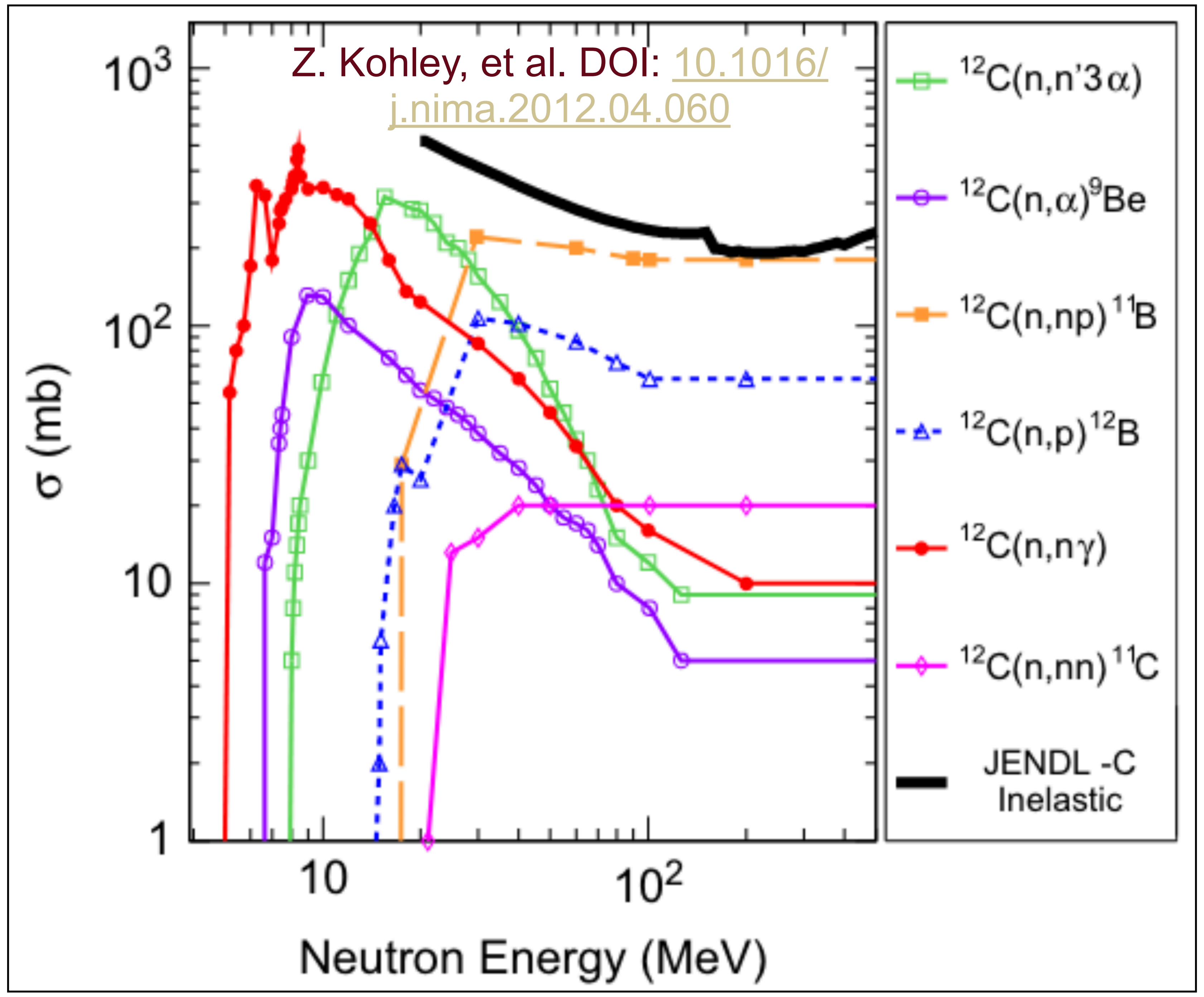
- Base simulation produces up to 40% more neutrons as compared to data
  - De-excitation photons produced by neutron inelastic scattering (medium red) are concentrated at low energy where the simulation excess is the greatest





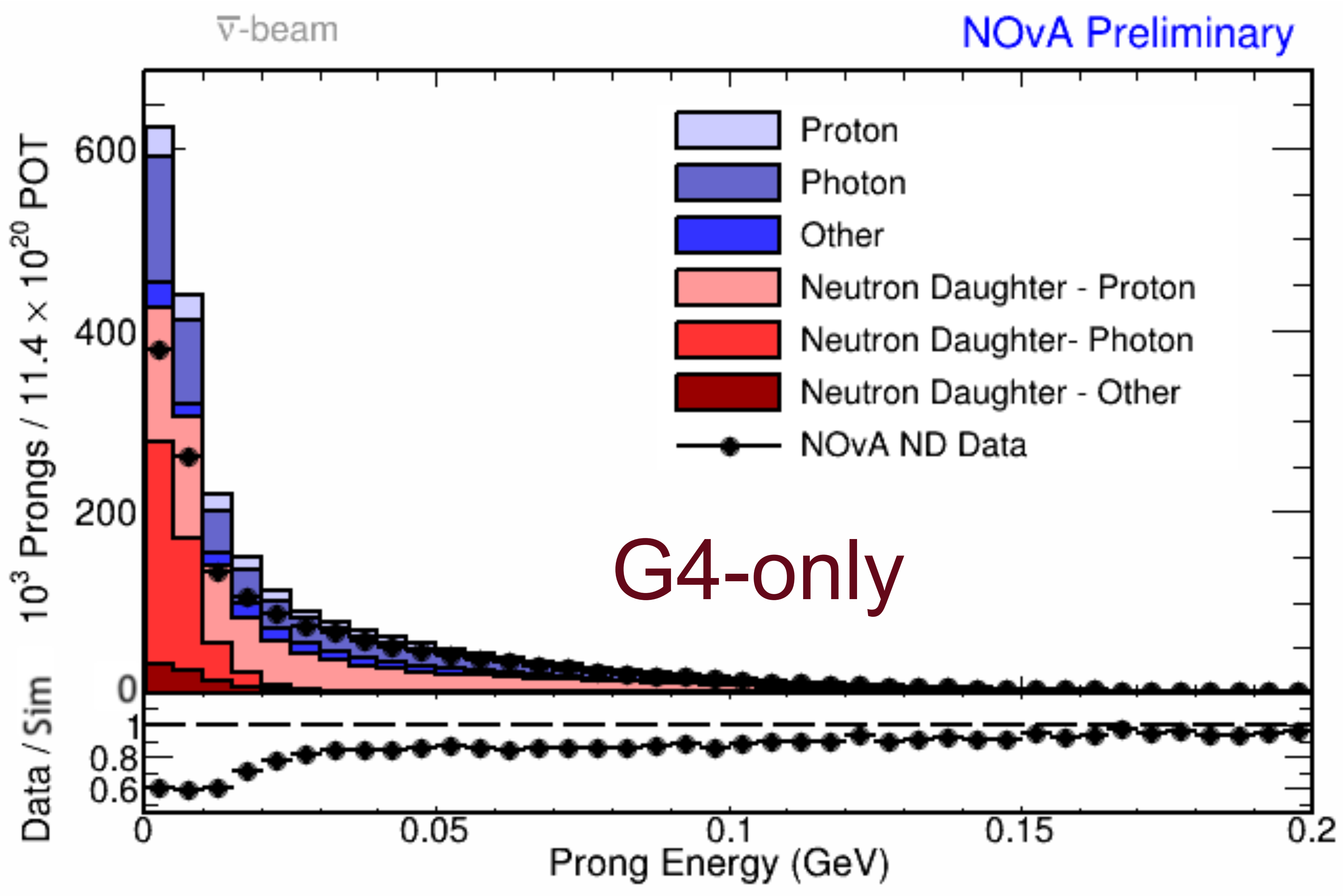
Alternative neutron inelastic model

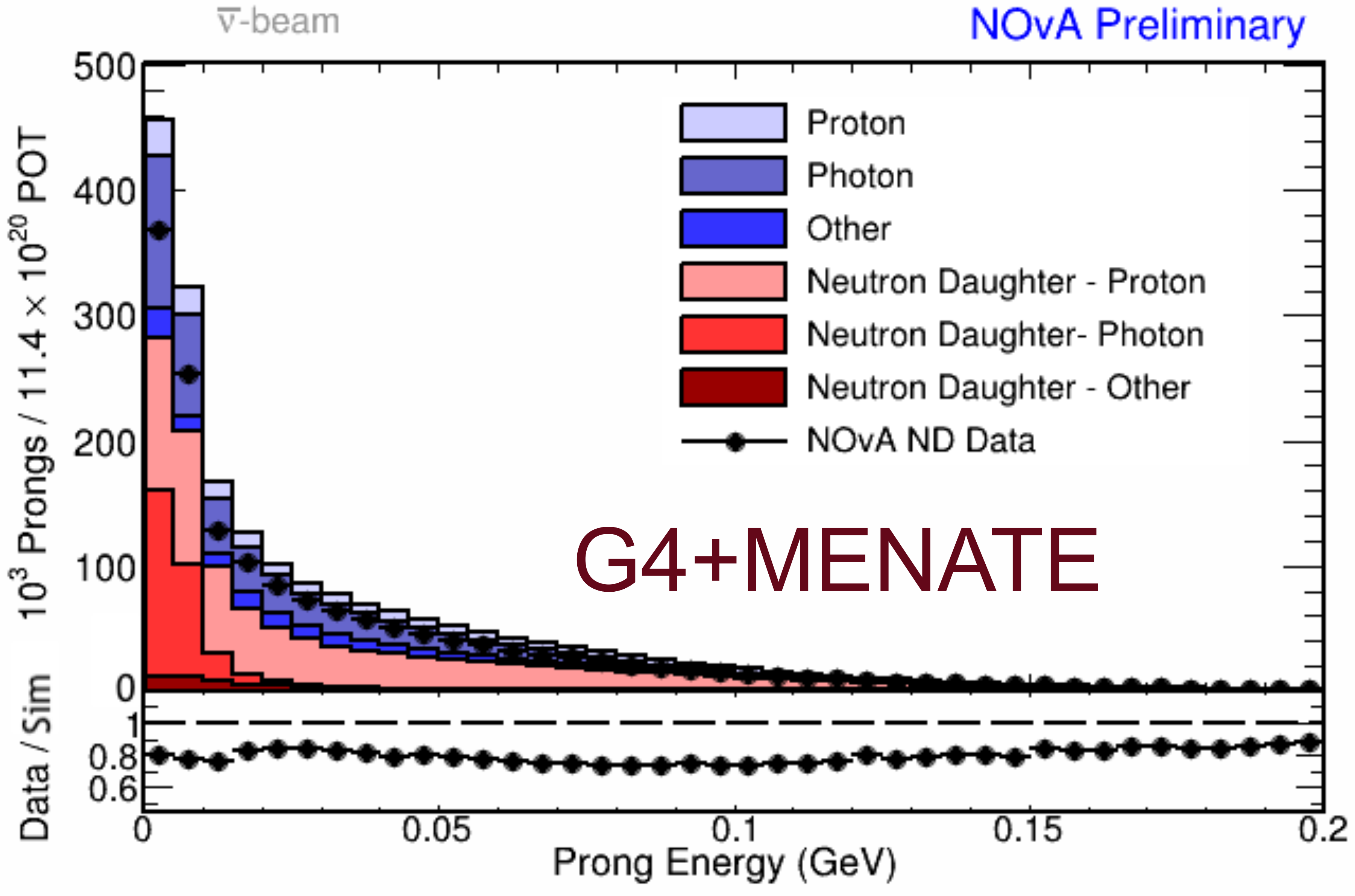
- De-excitation photons produced by Geant4:
  - The HP model: determines outgoing particles based on measurements (limited data)
  - Intranuclear cascade: theory-driven and statistically determines outgoing particles while using the overall cross-section
- MENATE extends the ethos of the HP model to higher energies
  - But only for neutron-on-carbon interactions (that's what we have data for)
  - Limits n+^{12}C to only 6 final inelastic states
  - Our implementation integrates directly with Geant4



Comparing to data

- MENATE reduces the over-simulation in the most populous bins
  - Photon production is significantly decreased
- It increases the over-simulation at higher energies
  - Proton production is slightly increased
- Overall, the data-simulation ratio is flatter, but there is still a significant over-simulation
  - Only addressing neutron-on-carbon; there are other targets and projectiles





Comparing to data

- MENATE reduces the over-simulation in the
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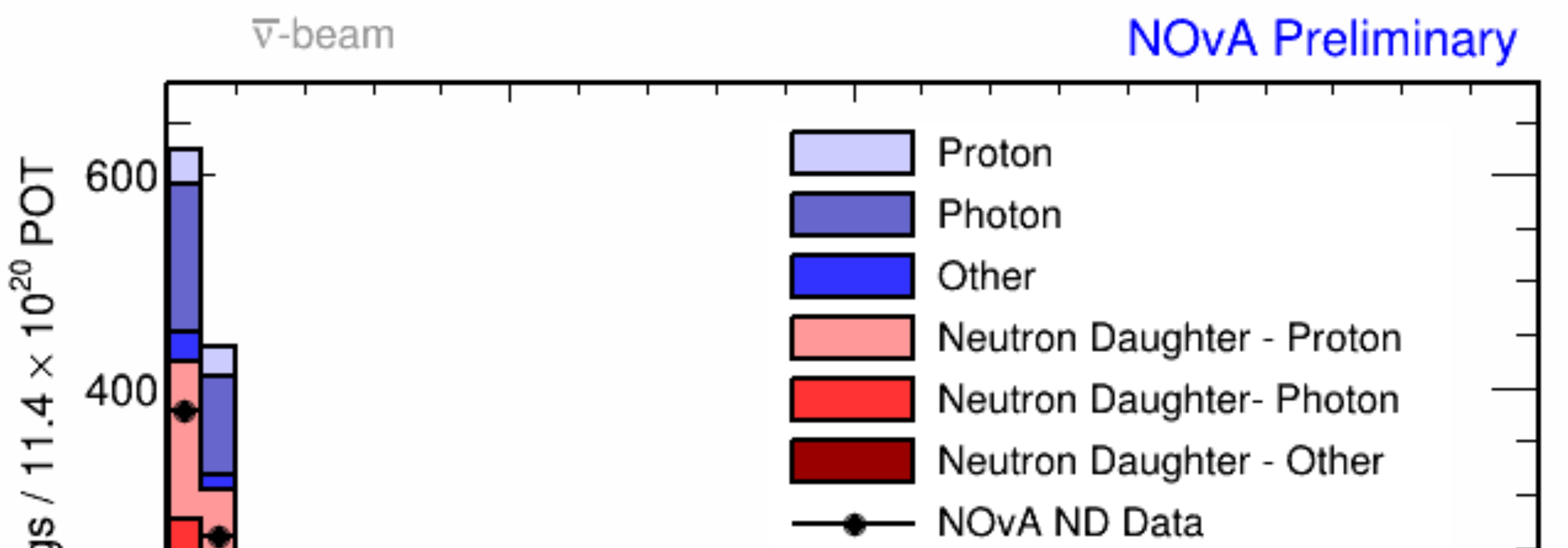
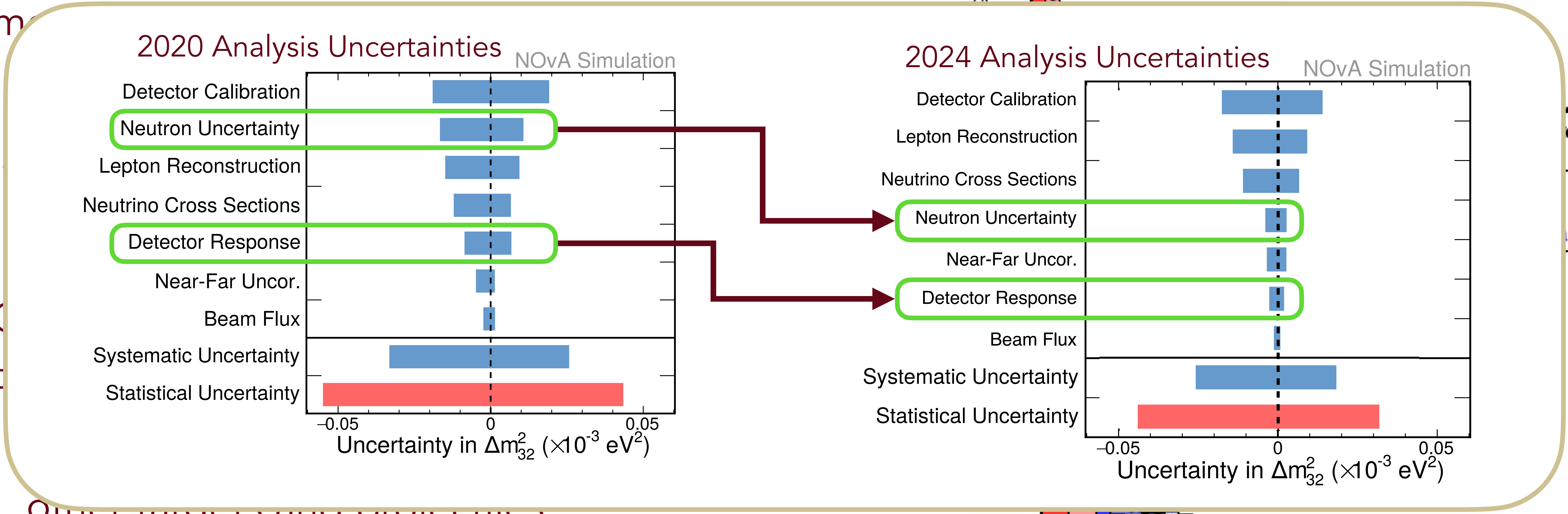
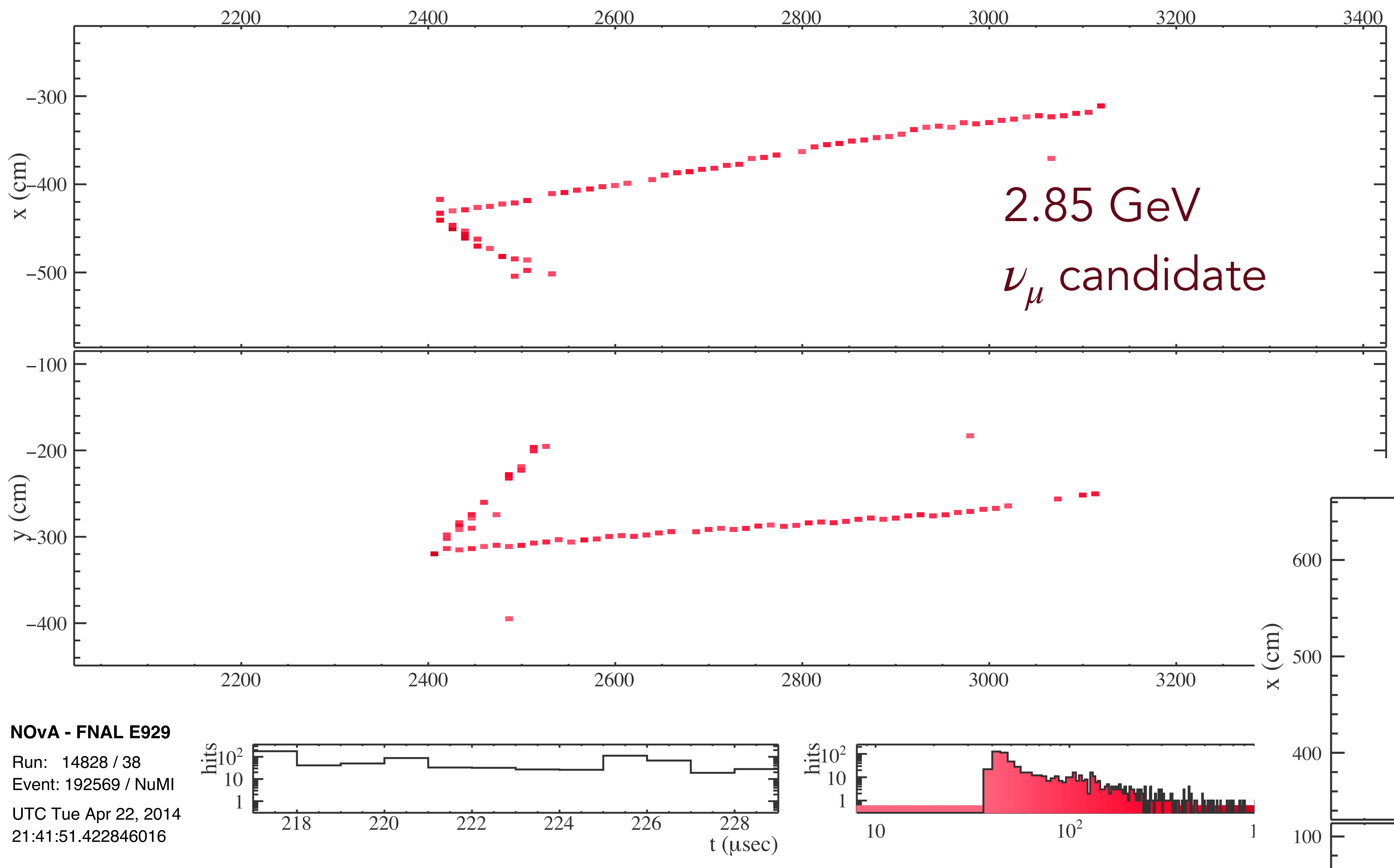
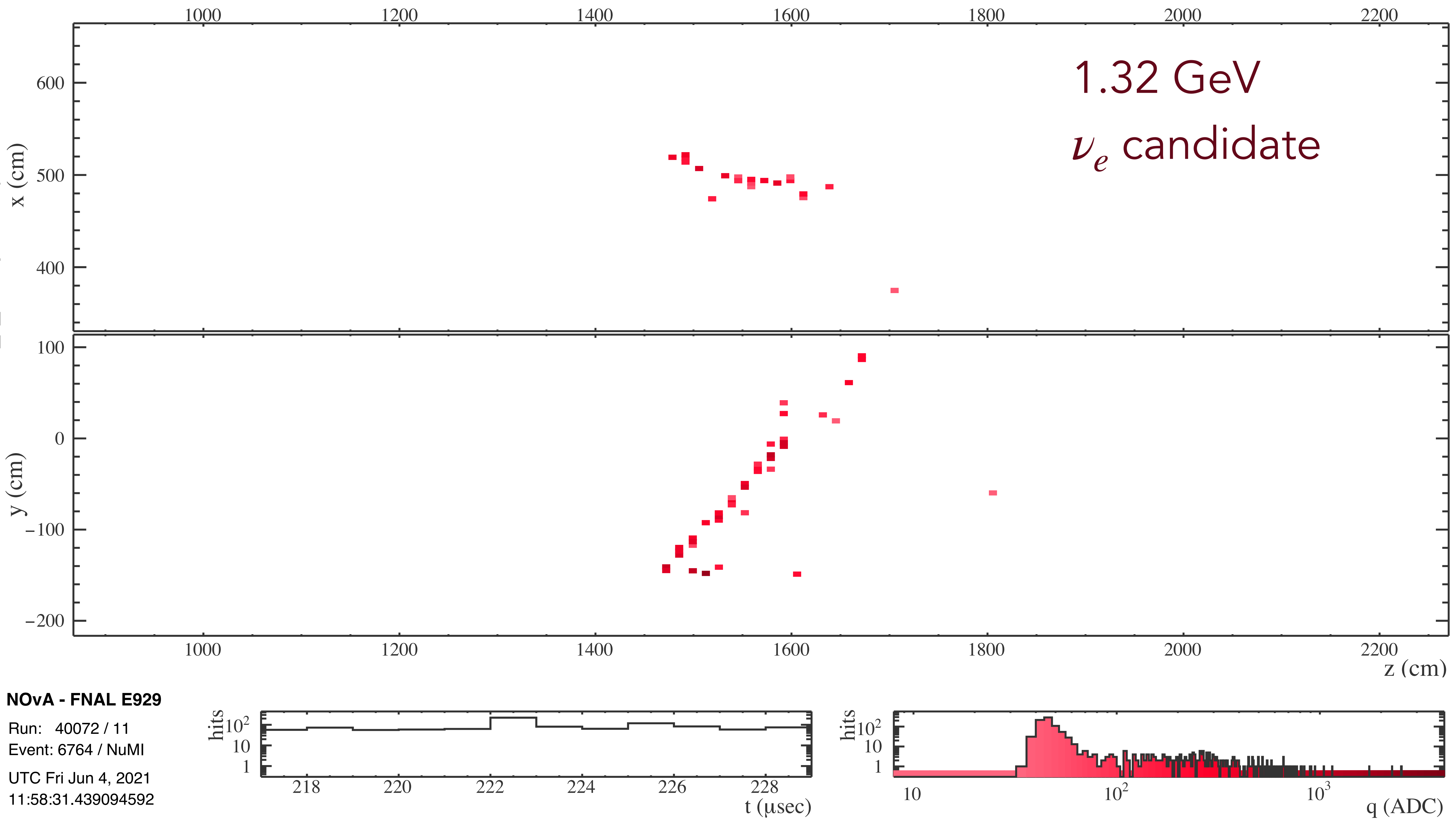




Results

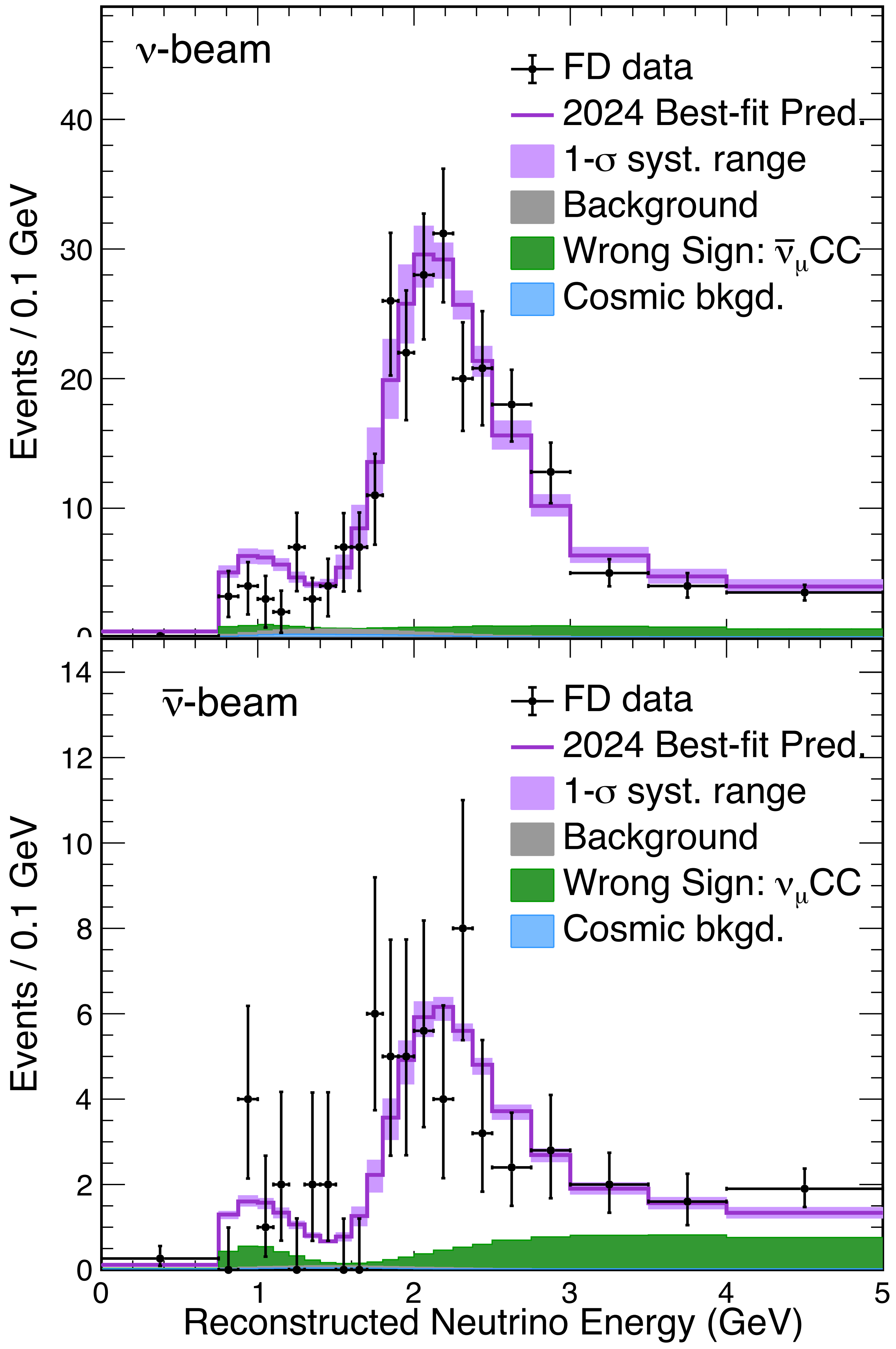

2.85 GeV
ν_μ candidate
x (cm)
y (cm)
NOvA - FNAL E929
Run: 14828 / 38
Event: 192569 / NuMI
UTC Tue Apr 22, 2014
21:41:51.422846016
hits
t (µsec)


1.32 GeV
ν_e candidate
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 40072 / 11
Event: 6764 / NuMI
UTC Fri Jun 4, 2021
11:58:31.439094592
hits
t (µsec)
q (ADC)

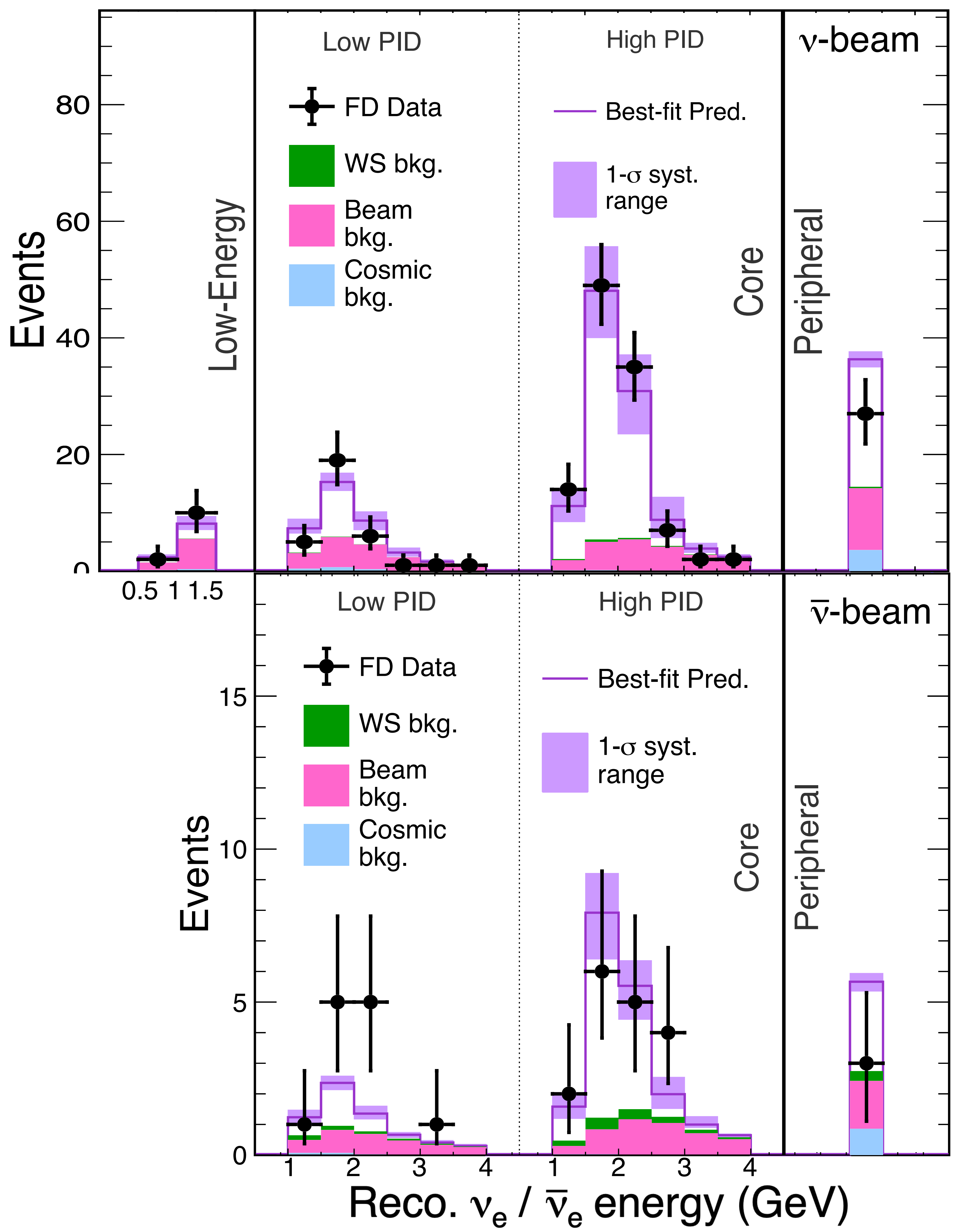
FD data

Sample	Num. Events	Background
ν_μ	384	11.3
$\bar{\nu}_\mu$	106	1.7
ν_e	181	61.7
$\bar{\nu}_e$	32	12.2

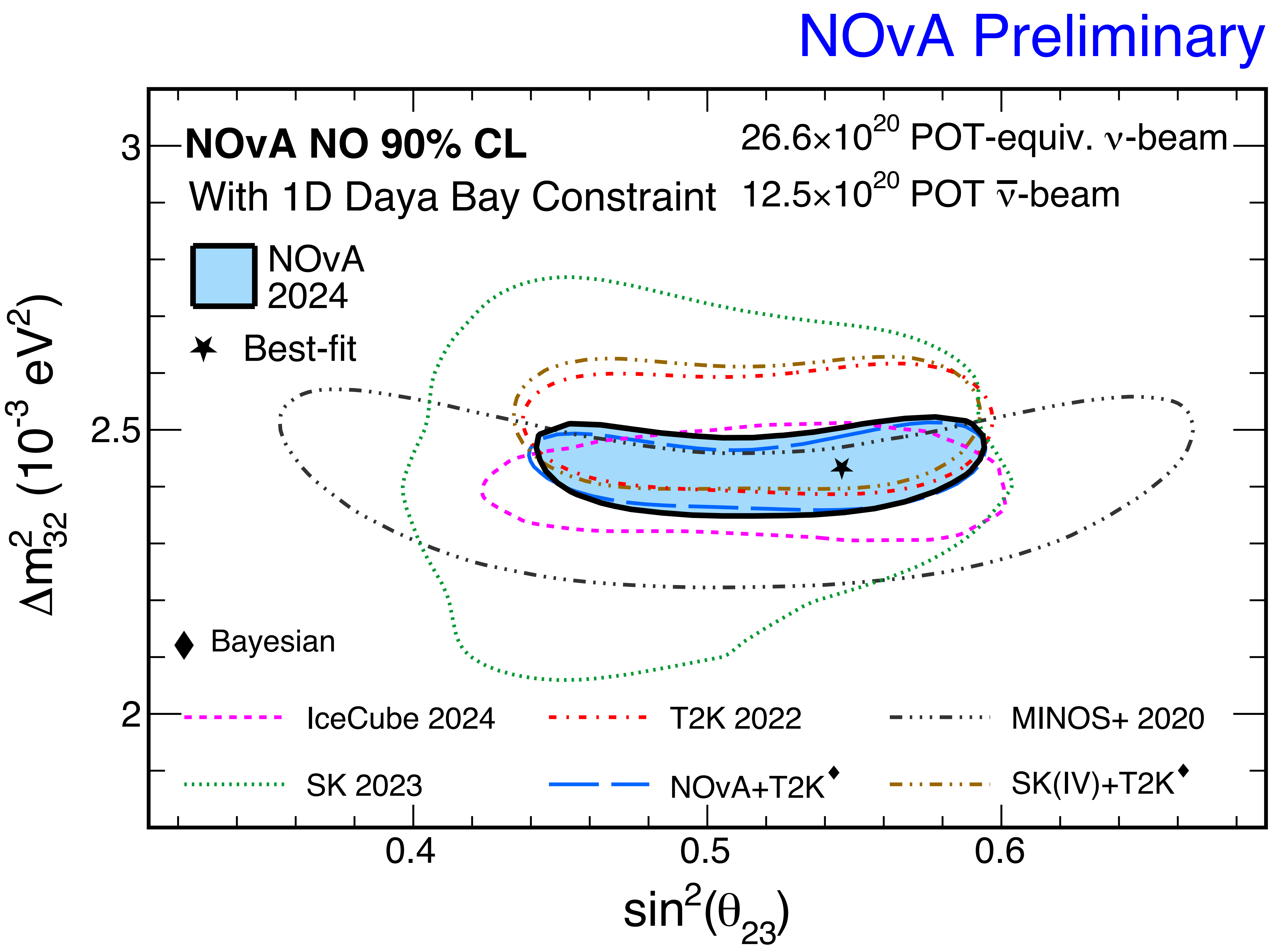
ν_μ



ν_e



Frequentist results

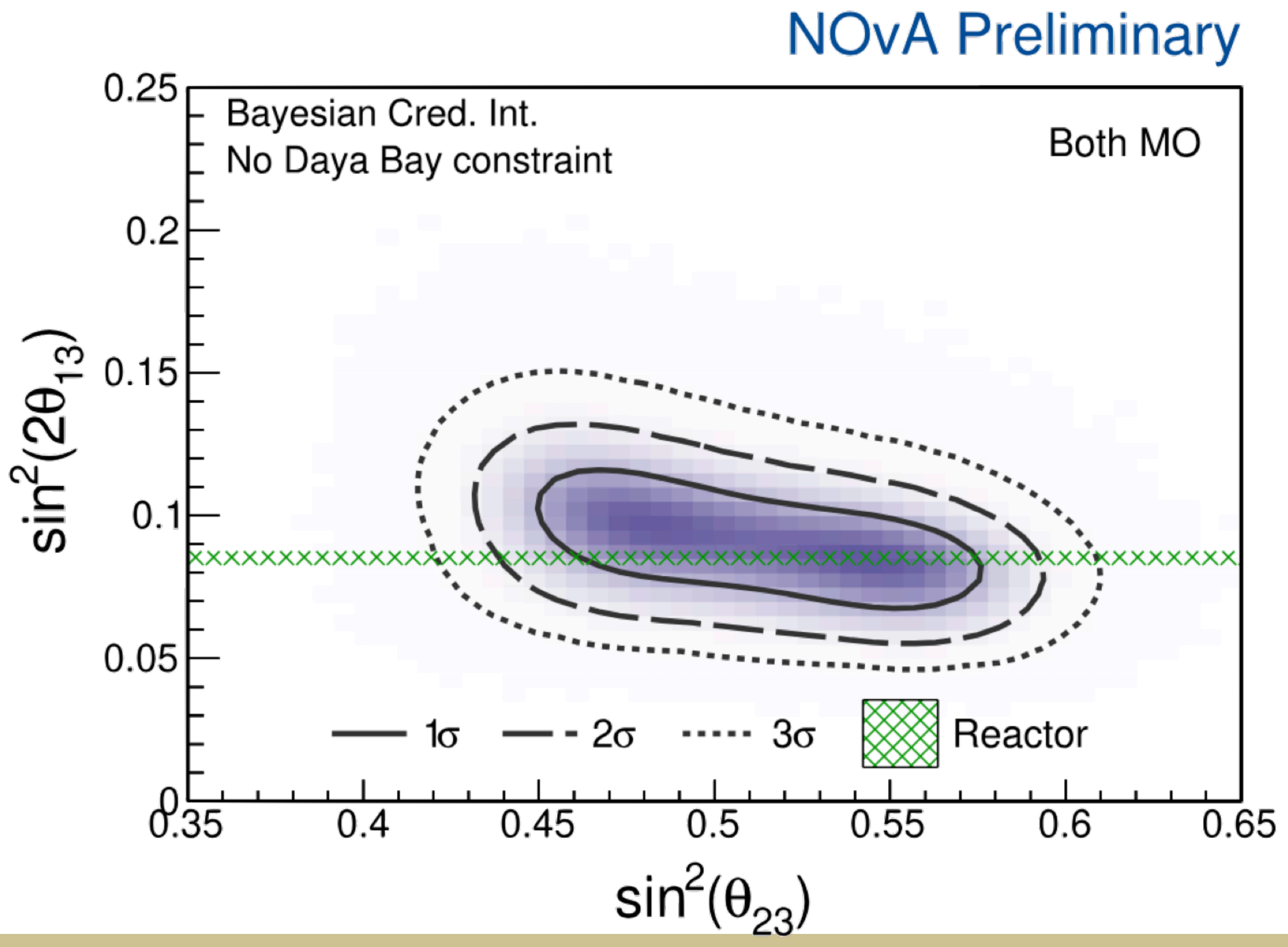


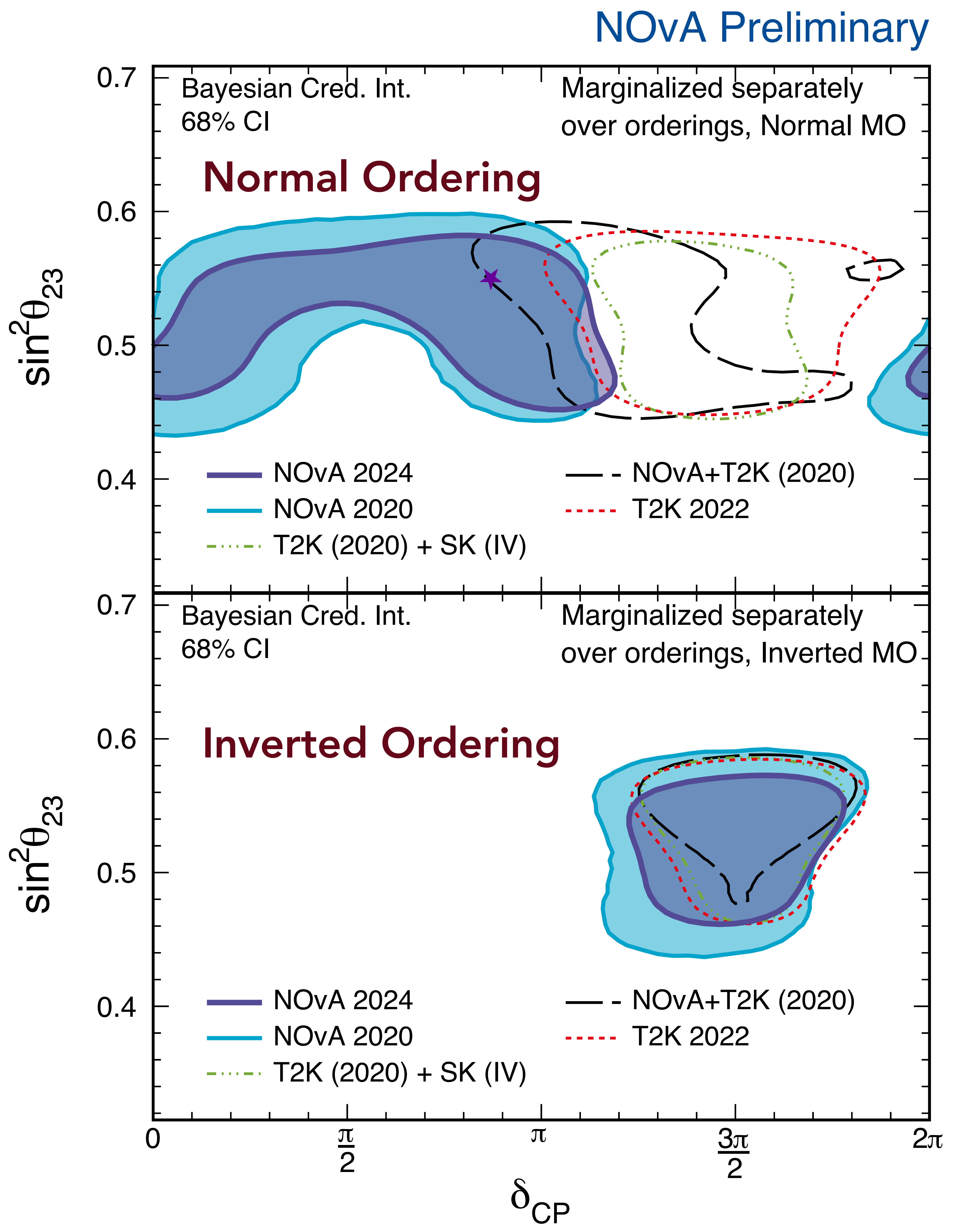
Parameter	Best-fit	Normal Ordering Preference (σ)	
$\sin^2(\theta_{23})$	$0.546^{+0.032}_{-0.075}$	W/ 1D Daya Bay constraint	p-value 0.1731 $1.36\,\sigma$
$\Delta m^2_{32}\ (10^{-3}\,\text{eV}^2)$	$2.433^{+0.035}_{-0.036}$	W/ 2D Daya Bay constraint	p-value 0.1158 $1.57\,\sigma$
$\delta_{CP}\ (\pi)$	0.875		

- New result is consistent with previous measurements and other experiments
- Prefer the Upper θ_{23} octant and Normal Mass Ordering
- Most precise single-experiment measurement of Δm^2_{32}

Bayesian results

- Prefer CP conserving values of δ_{CP} in the normal mass ordering and CP violating values in the inverted
- Preference for Normal Mass Ordering and Upper θ_{23} Octant is enhanced by reactor constraints





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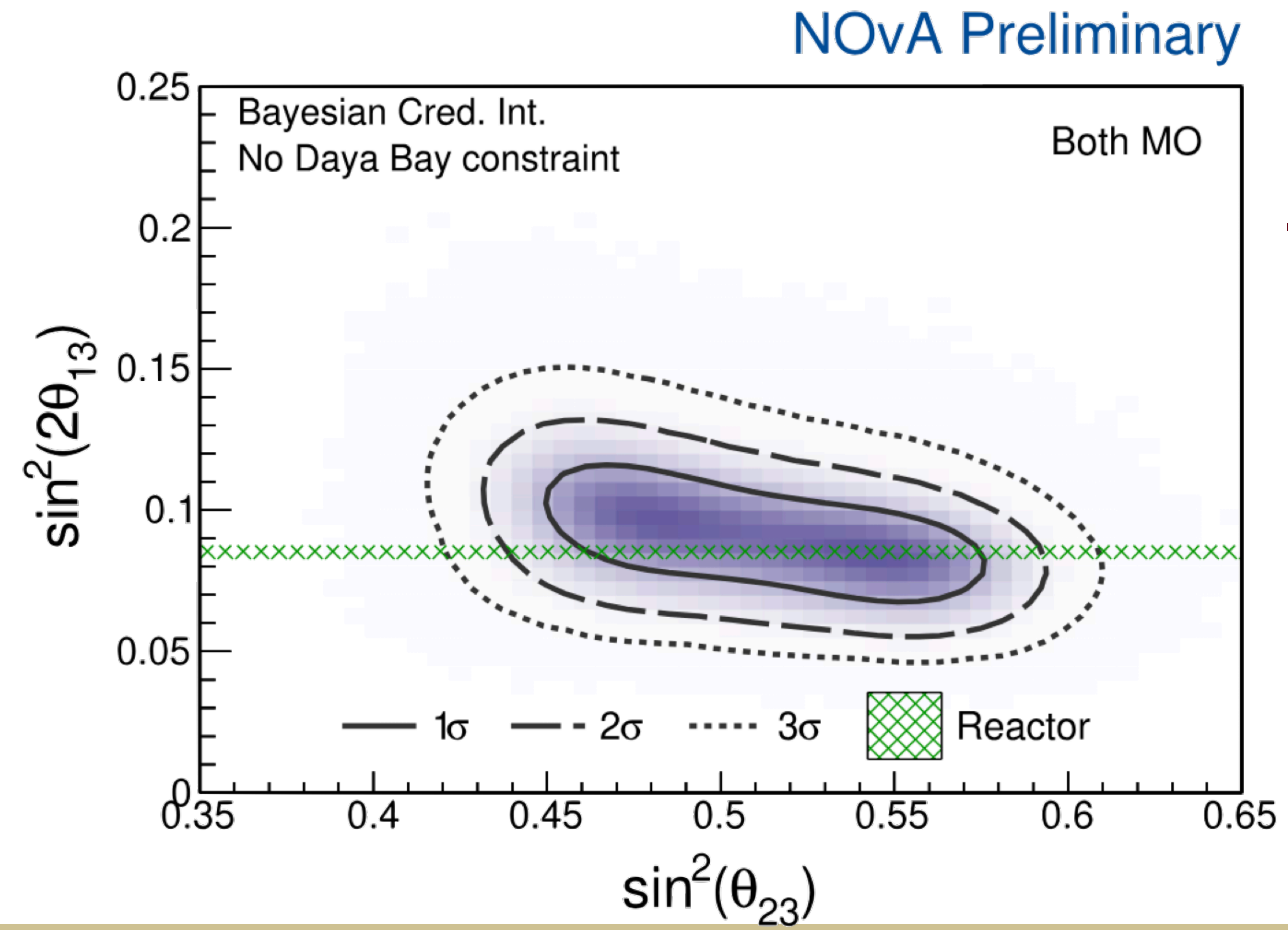
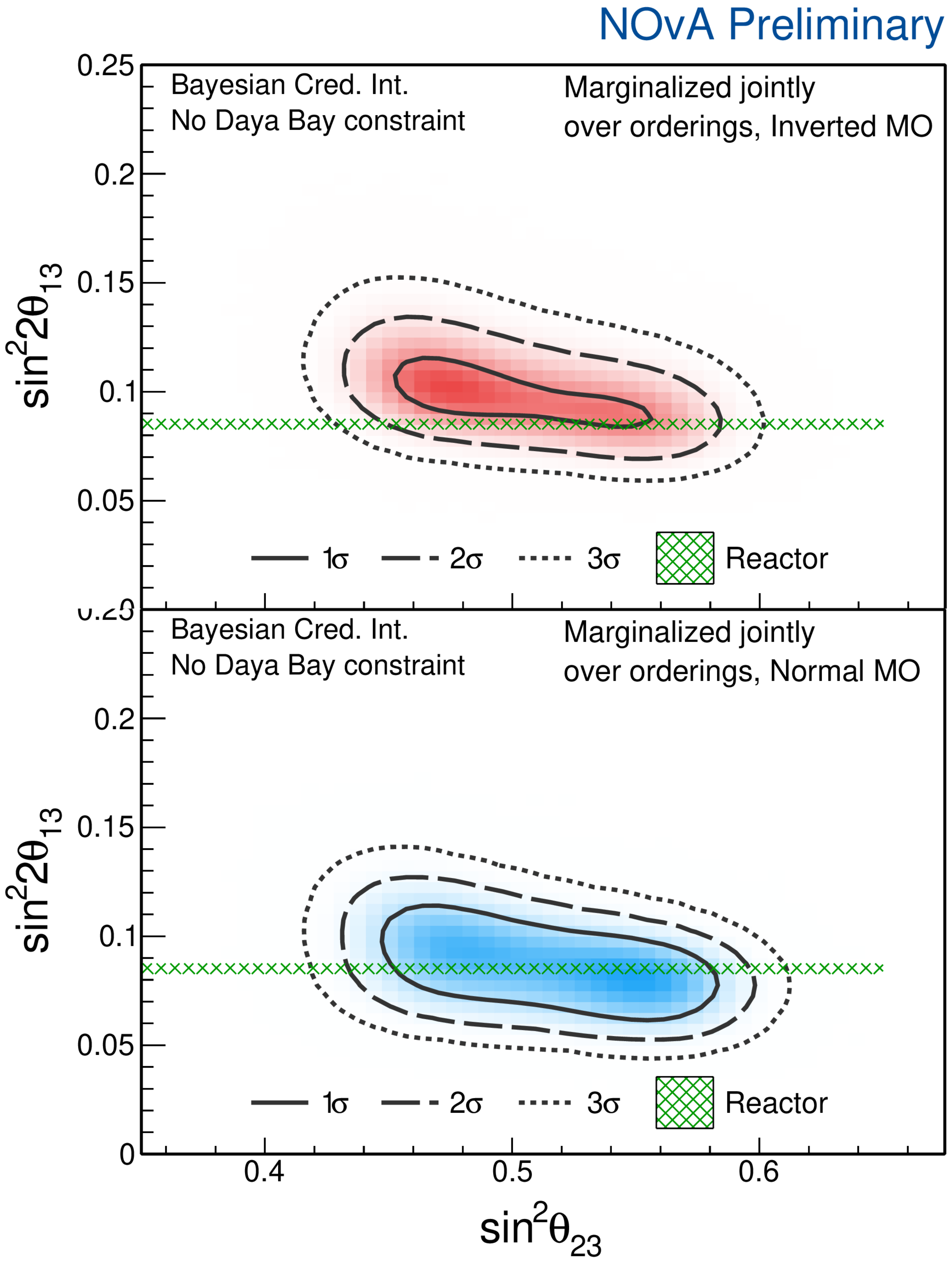
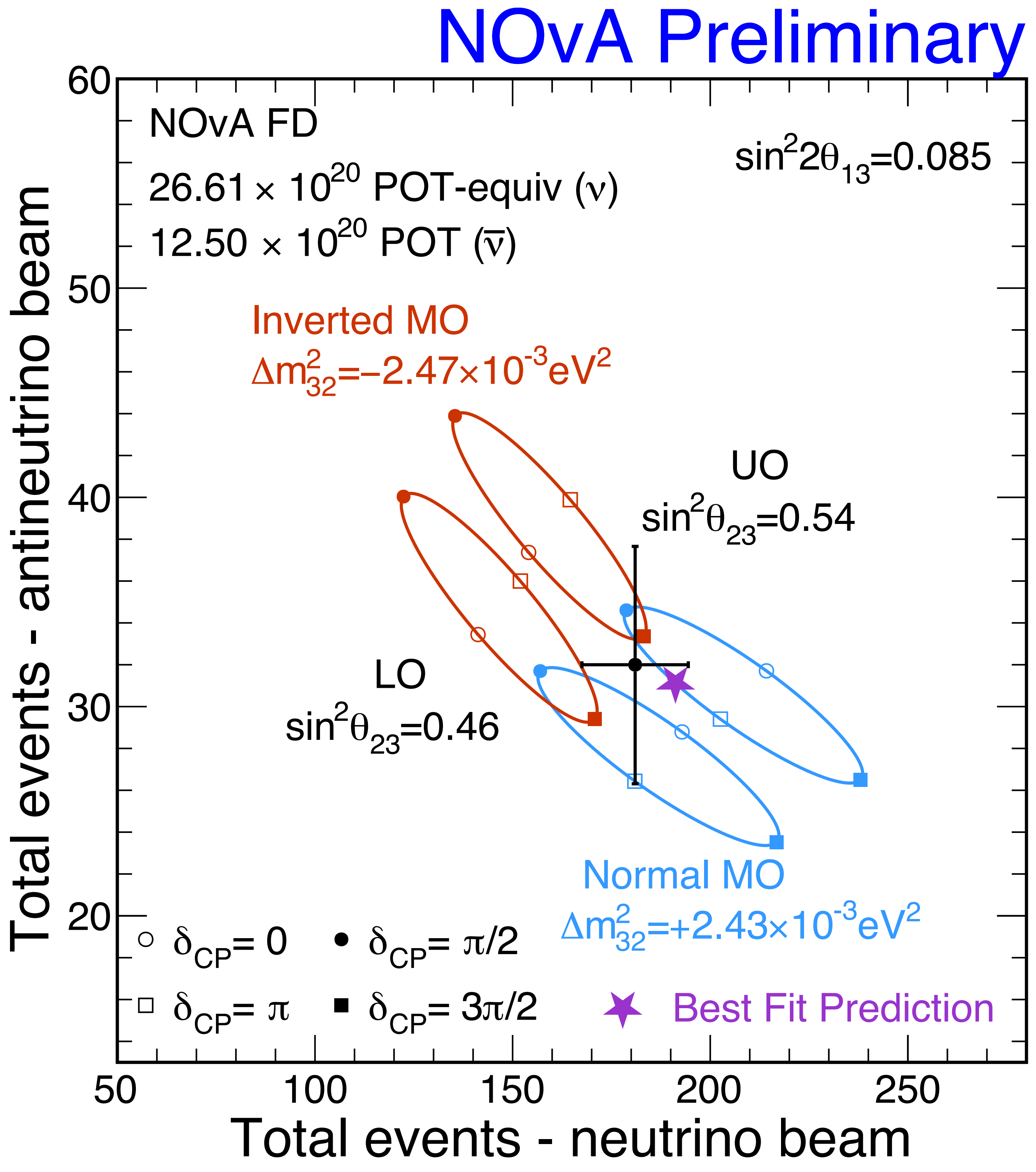


- NO preference at 87% posterior probability



Summary

- Newest NOvA results contain 2X more neutrino-mode data from 10 years of running
- Most most precise single-experiment measurement of Δm^2_{32}
  - Now the most precisely measured oscillation parameter
- Slight preference for normal mass ordering and upper θ_{23} octant, but in a highly degenerate region
- We are analyzing results from a Test Beam run to help constrain our largest systematic uncertainty



Summary

Thanks!

This document was prepared by NOvA using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by FermiForward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

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ary
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rediction
50 100 150 200 250
Total events - neutrino beam

Backups

Neutrino Oscillations

- Neutrino are observed in "flavor states" $(\nu_e, \nu_\mu, \nu_\tau)$
- Which are superpositions of "mass states" (ν_1, ν_2, ν_3)
  - The mixing is described by the unitary matrix: U_{PMNS}
- As a neutrino propagates, the mass states interfere causing the flavor to change from one type to another
- Oscillations depend on:
  - Elements of U_{PMNS}
  - Distance of travel / neutrino energy
  - Mass (squared) splittings

$$|\nu_\alpha(\mathbf{x}, t)> = \sum_{i=1}^{3} U^*_{\alpha,i} |\nu_i(\mathbf{x}, t)>$$

$$P(\nu_\alpha \to \nu_\beta) = f(U_{PMNS}, L/E, \Delta m^2_{ij})$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

The PMNS Matrix

- With three flavor states and three mass states, U_{PMNS} is a 3 X 3 matrix

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

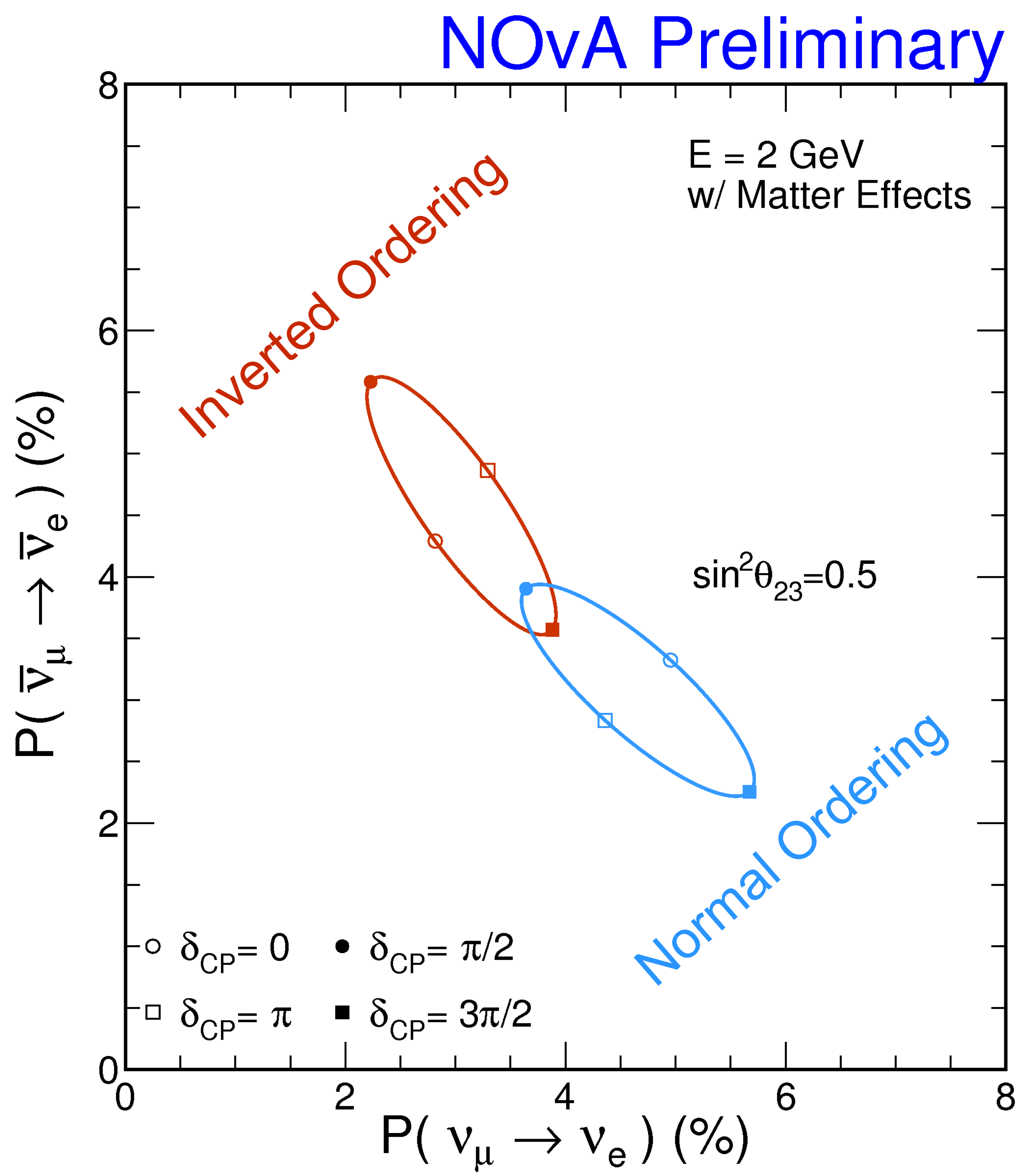
$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$$

- Three mixing angles: θ_{12}, θ_{13}, θ_{23}; and a (potentially) CP-violating phase: δ_{CP}
  - CP = charge inversion + parity inversion
    - Charge transformation: change particle to antiparticle (and vice versa)
    - Parity transformation: mirror all spatial coordinates
  - CP violation in the neutrino sector might explain why the universe is matter-dominated

Decoding our measurements

$\overset{(-)}{\nu}_e$ appearance

- Oscillations in matter pull the ellipses apart
  - Due to coherent forward scattering on electrons
  - NO increases the neutrino oscillation probability and suppresses antineutrino oscillations
  - IO is reversed



Decoding our measurements

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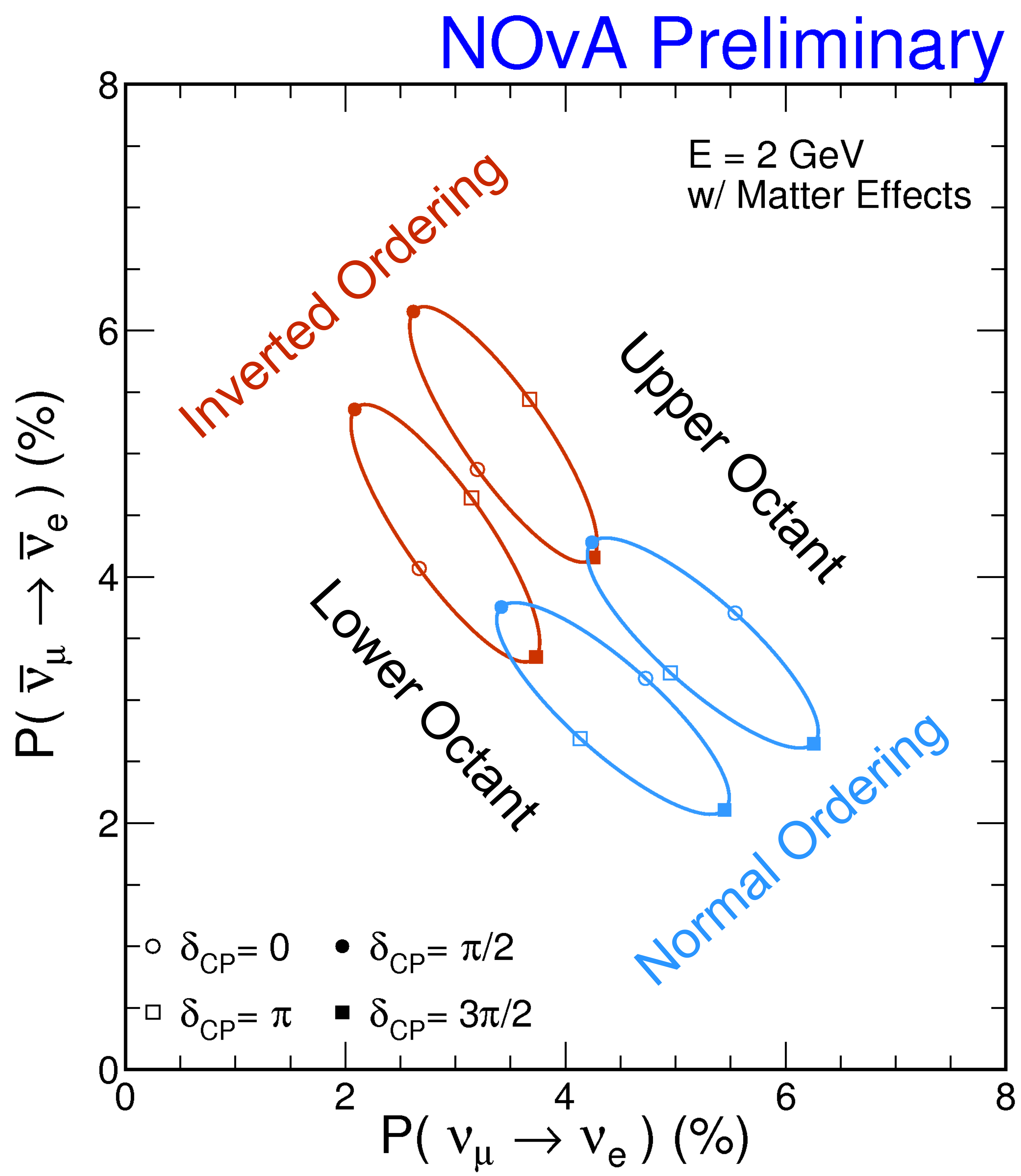
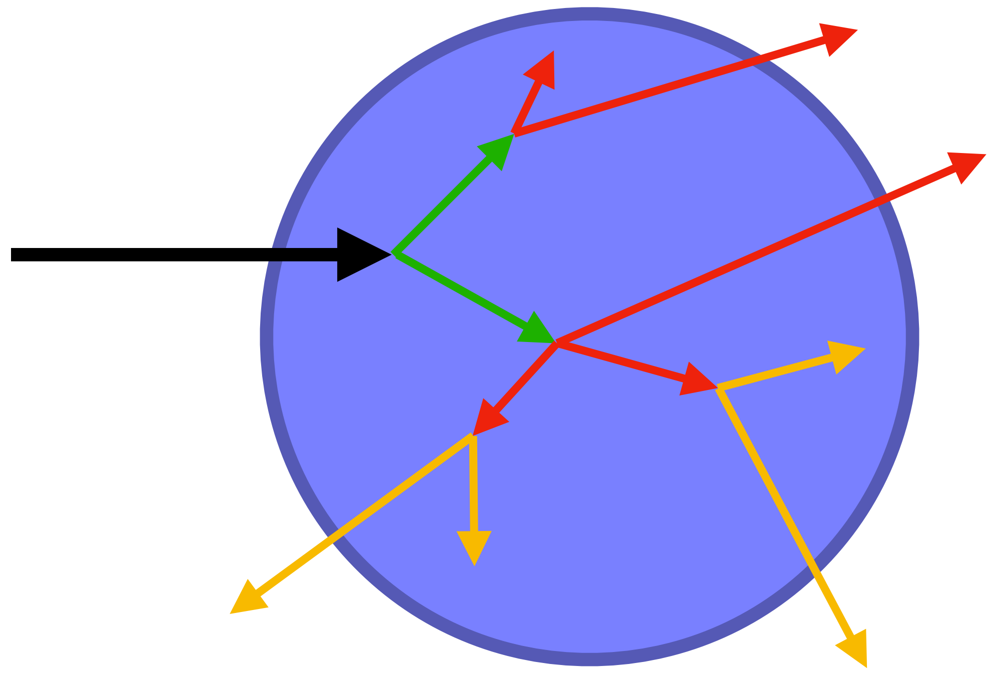
- If θ_{23} does not produce maximal mixing then the choice of octant (< or > 45°) further splits the ellipses

- There are still degenerate regions near the middle



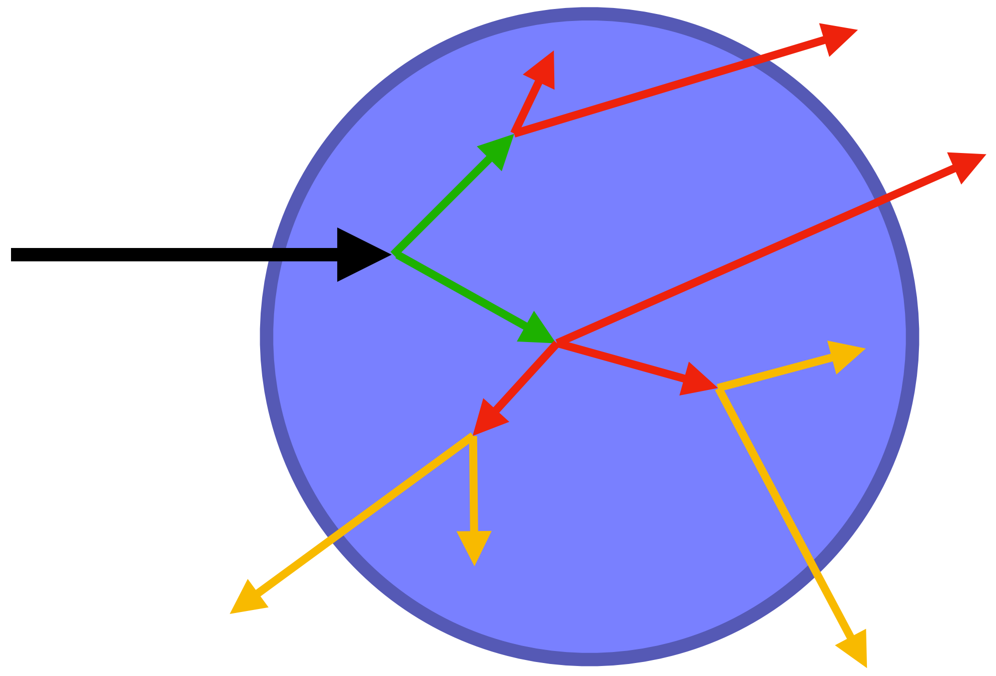
Neutron inelastic scattering



- Geant4 uses two models based on KE
  - Below 20 MeV: Data-driven "High precision"
  - 20 MeV-10 GeV: Intranuclear cascade
- NOvA uses the Bertini intranuclear cascade, which is split into sub-models
  - Nucleon-nucleon interactions: basically two-body

Beam flux simulation → Neutrino interactions: GENIE → Particle propagation: Geant4 → Custom light model and electronics

Neutron inelastic scattering



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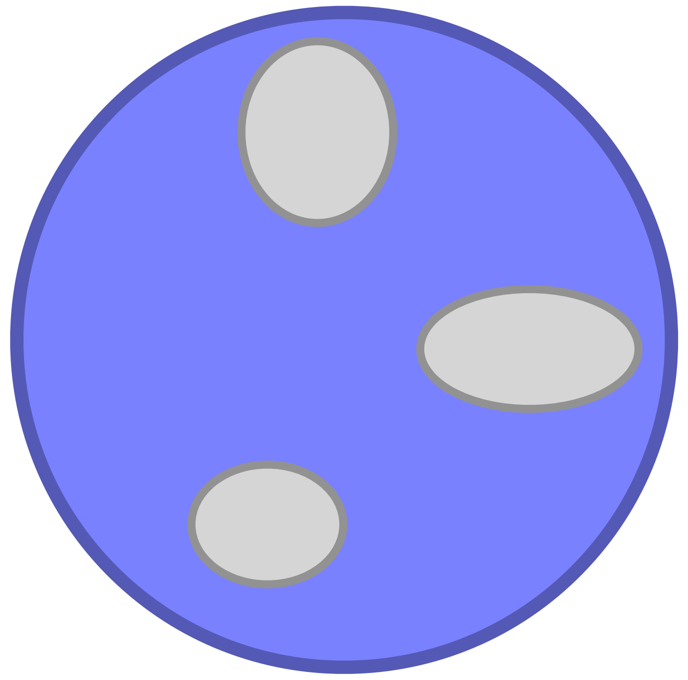
  - Pre-equilibrium: balances the residual excitons



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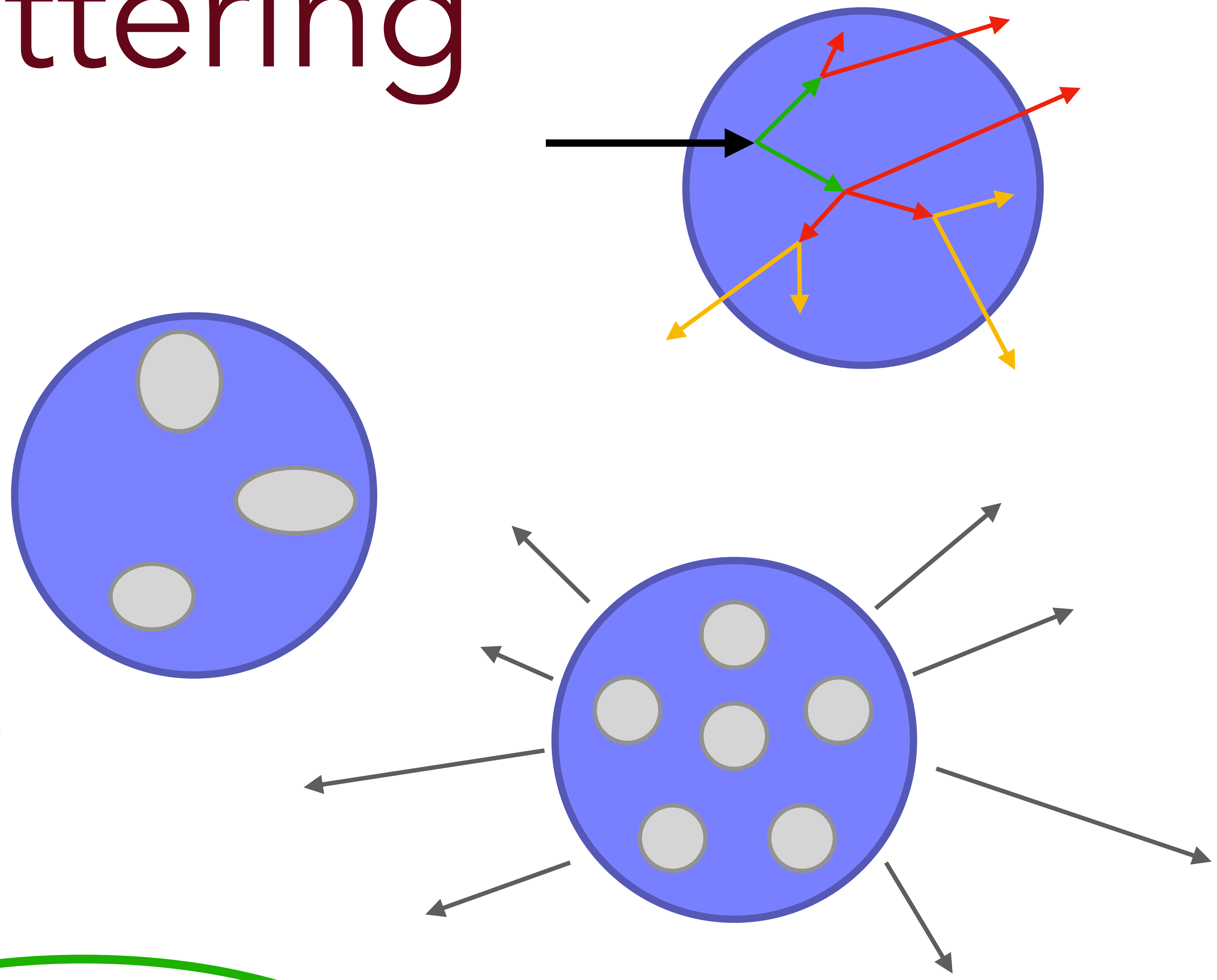
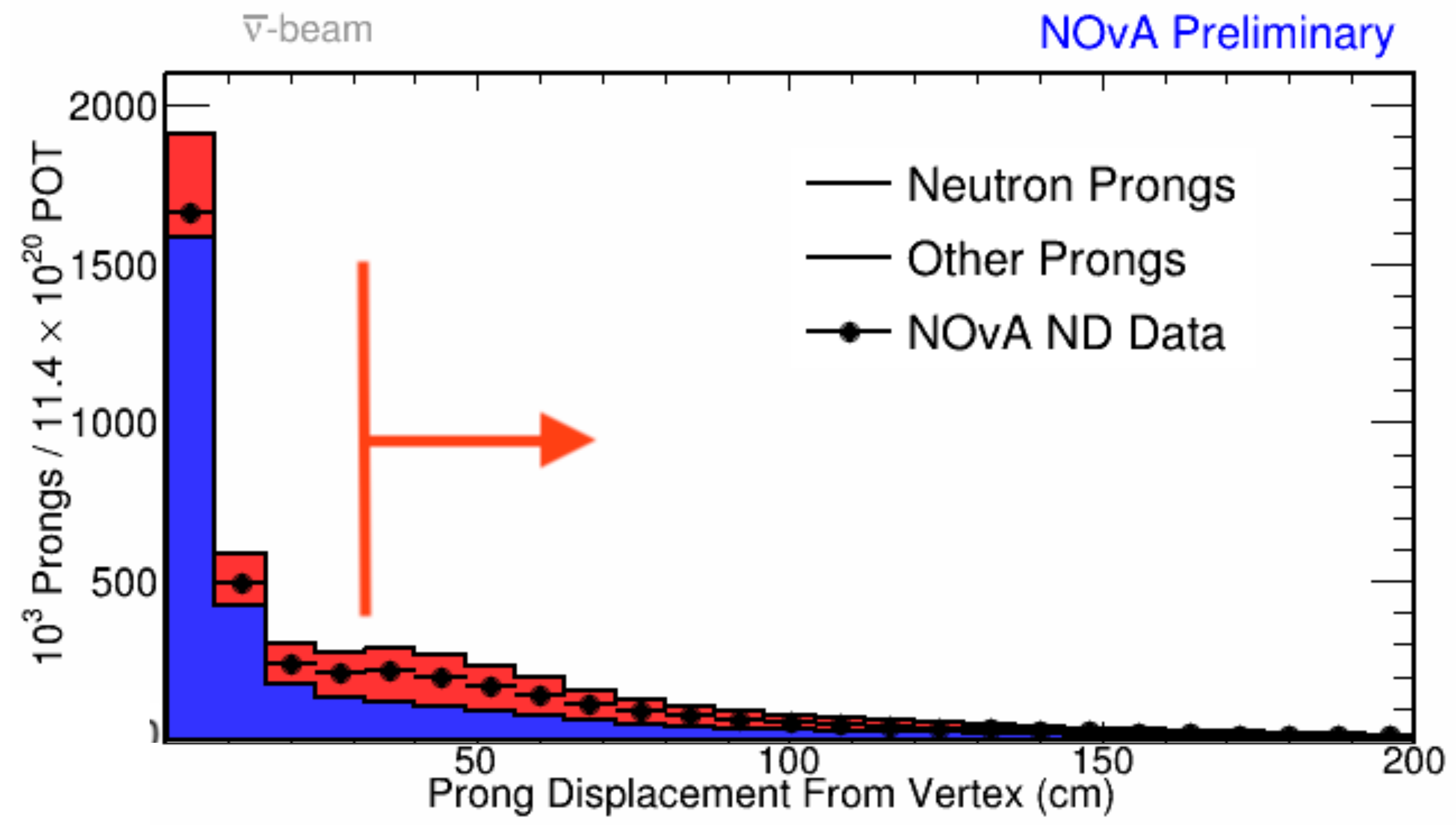
  - Nucleon-nucleon interactions: basically two-body
  - Pre-equilibrium: balances the residual excitons
  - Evaporation: heavy particles first, then photons

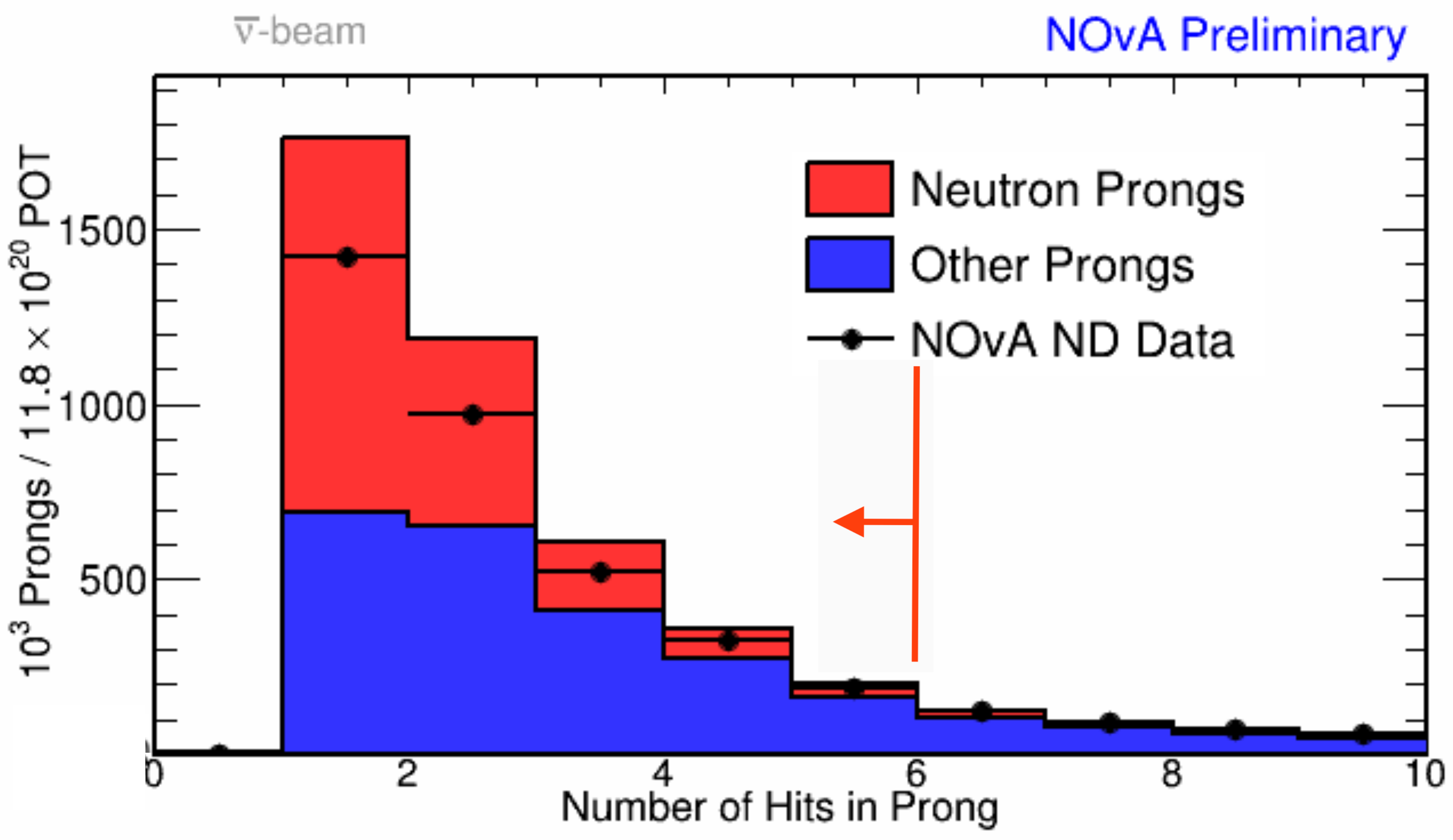


Beam flux simulation → Neutrino interactions: GENIE → Particle propagation: Geant4 → Custom light model and electronics

Selecting neutrons

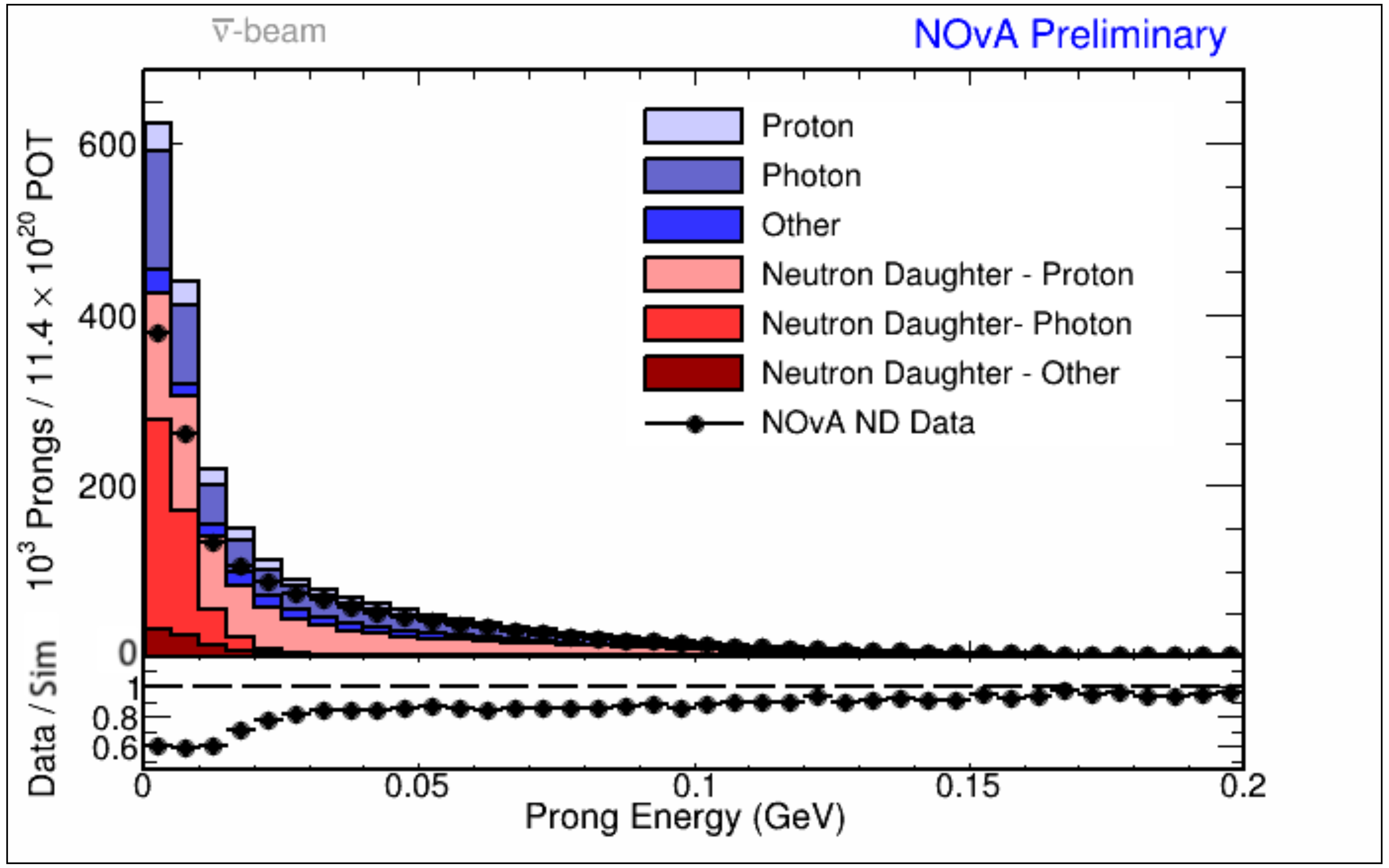
- Frequent elastic scattering means neutron-related-hits are typically far from the neutrino interaction vertex
  - Select only hit clusters that are > 20 cm away
- Neutron energy depositions are not highly correlated to their kinetic energies
  - Typically leave only a few visible hits
  - Require hit clusters to have fewer than 6 hits

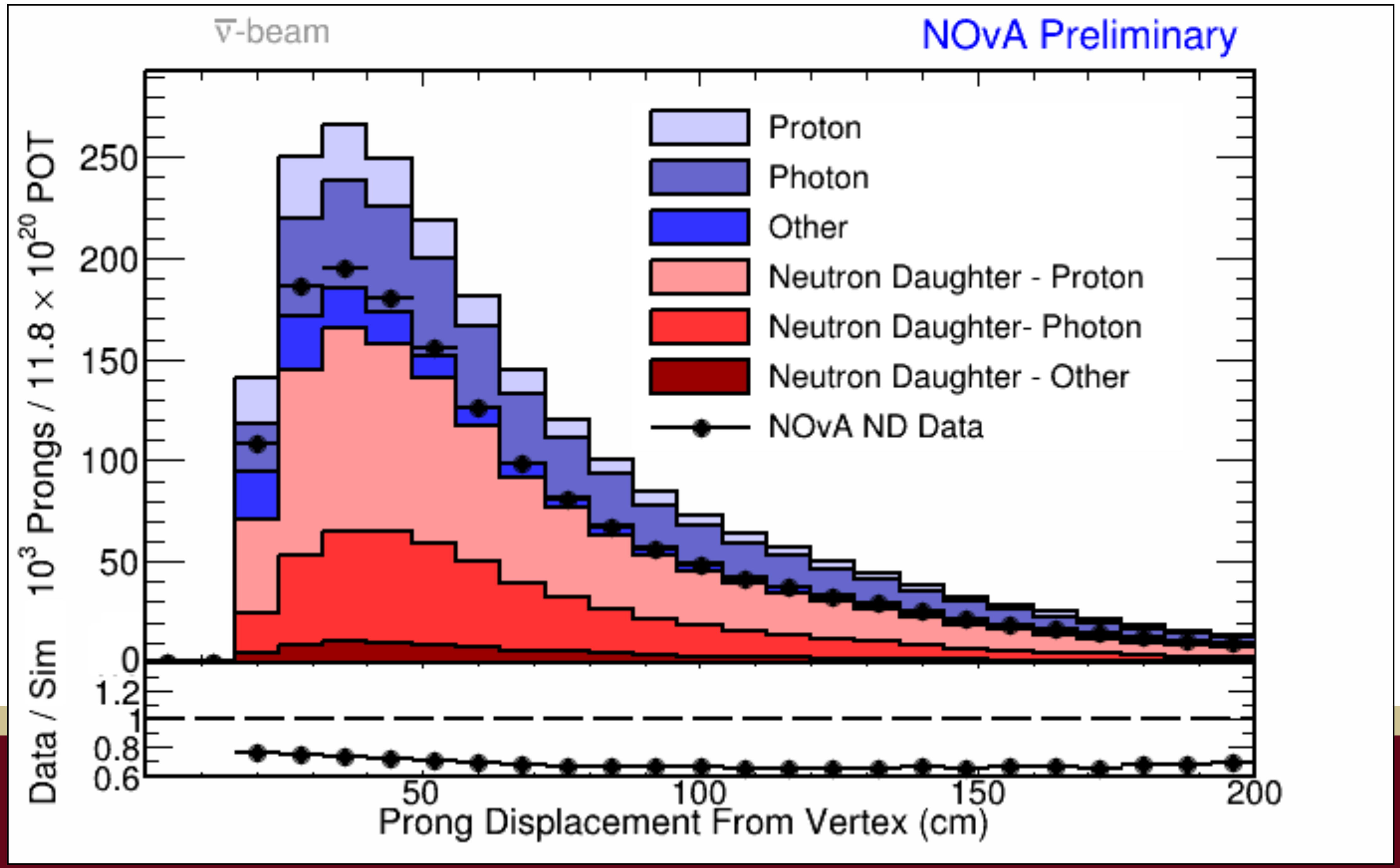




Selection results

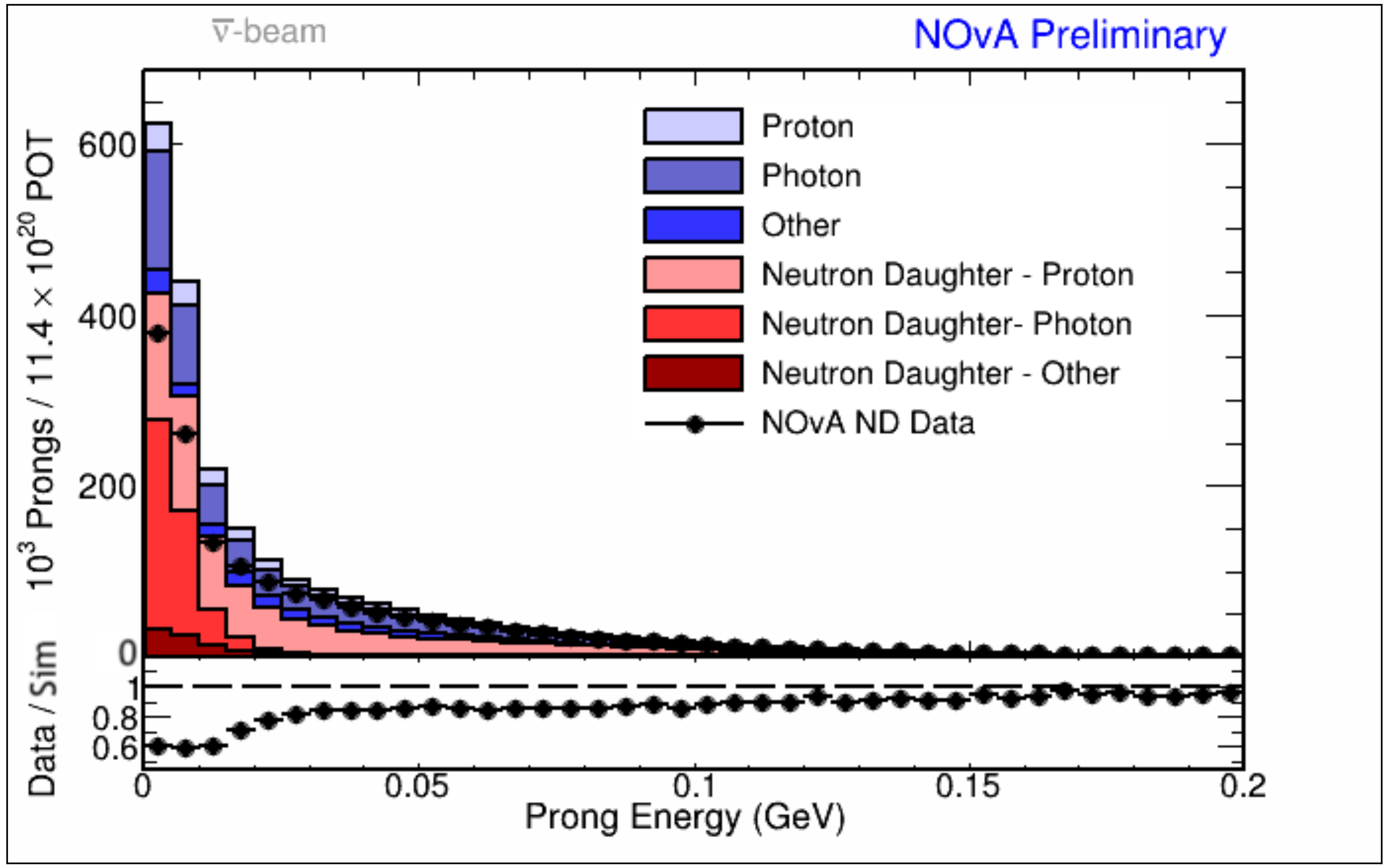
- Apply NOvA's standard $\bar{\nu}_\mu$ selection at the ND then perform neutron selection
  - 71% efficiency for selecting visible neutrons
  - Selected sample is 61% pure

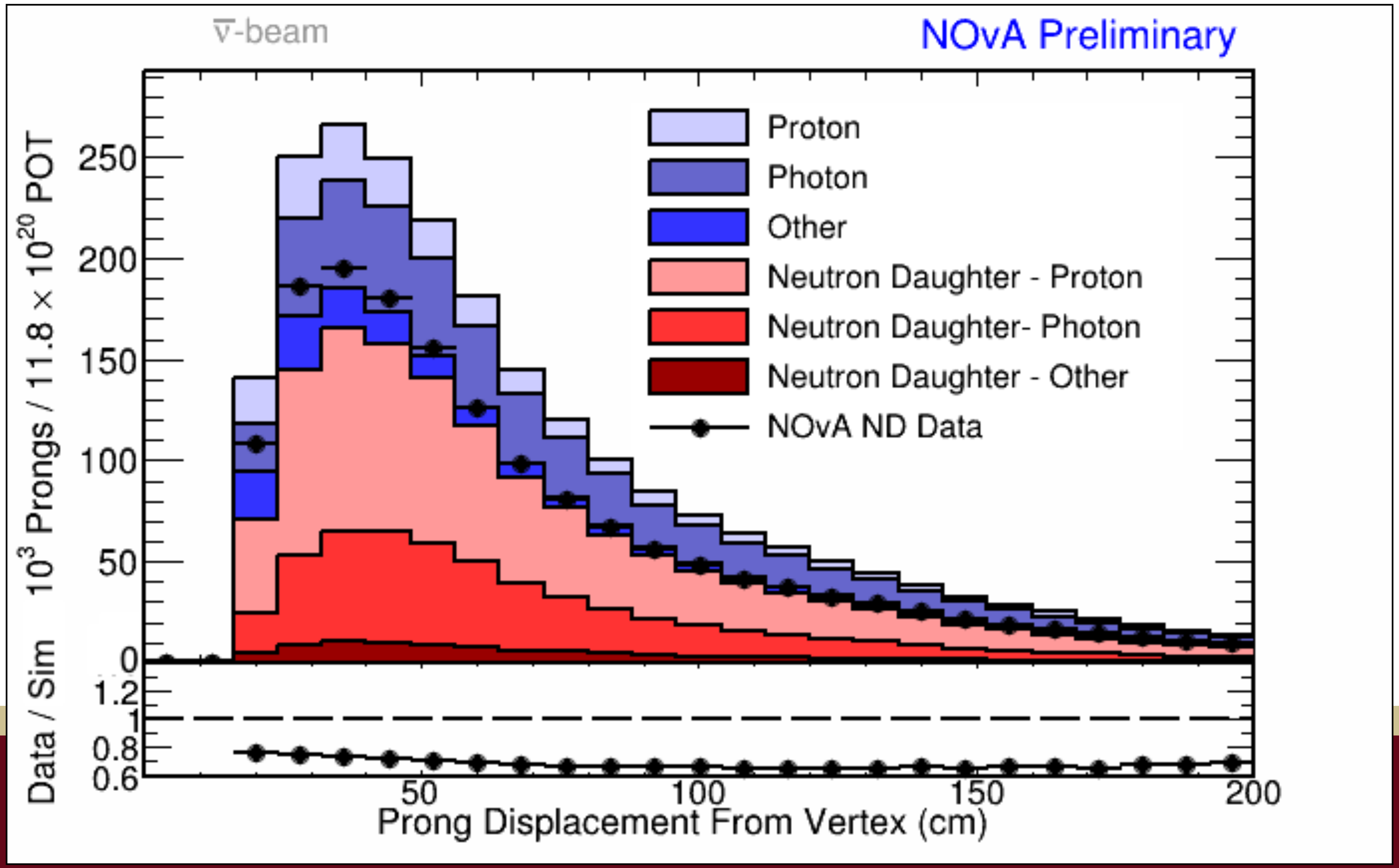




Selection results

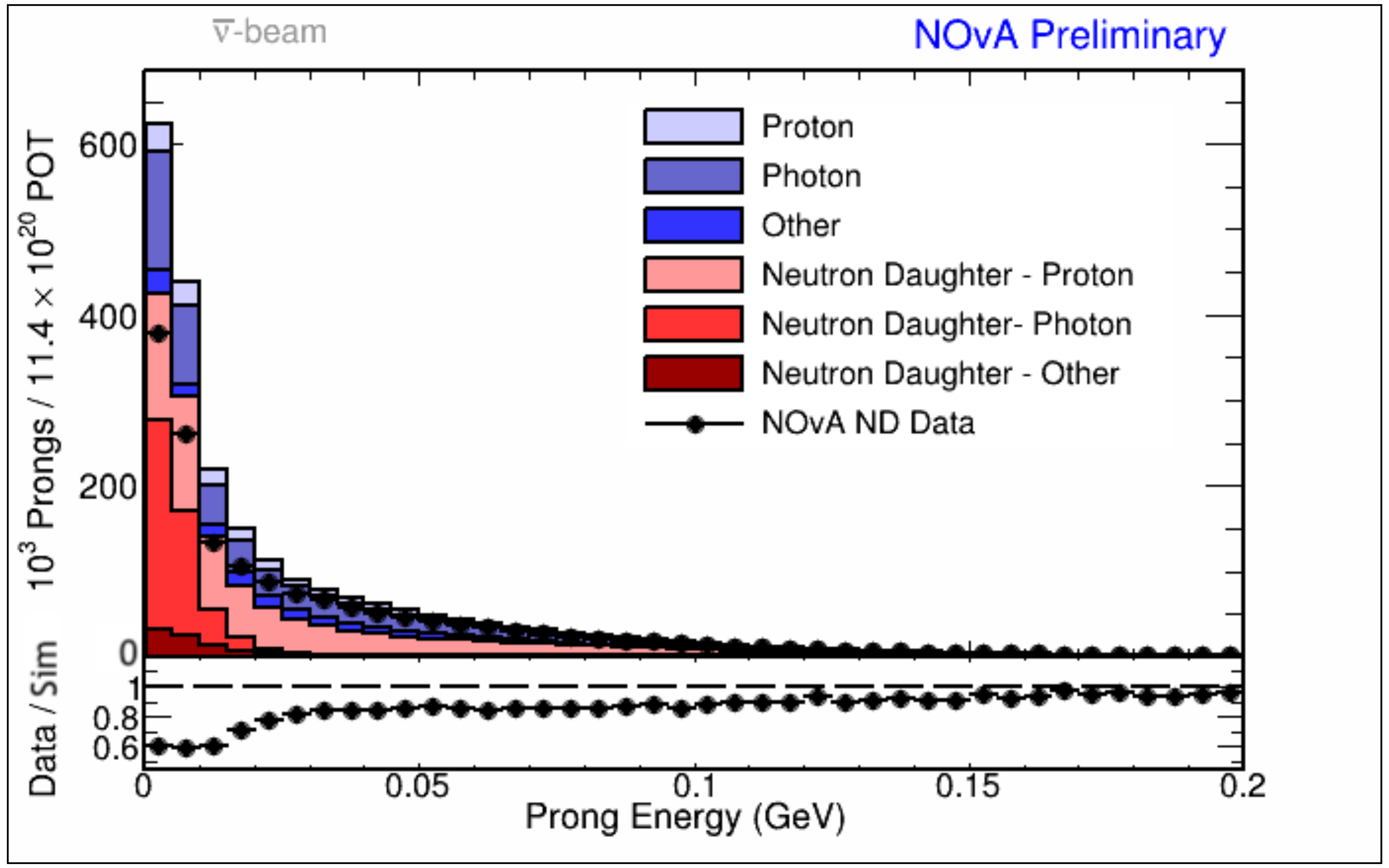
- Apply NOvA's standard $\bar{\nu}_\mu$ selection at the ND then perform neutron selection
  - 71% efficiency for selecting visible neutrons
  - Selected sample is 61% pure
- Simulation is broken down by particle type
  - Red shades are particles associated with a primary neutron
  - Blue shades are contamination from other primary particles
- Significant data-simulation discrepancy
  - Up to 40% in the lowest energy bins

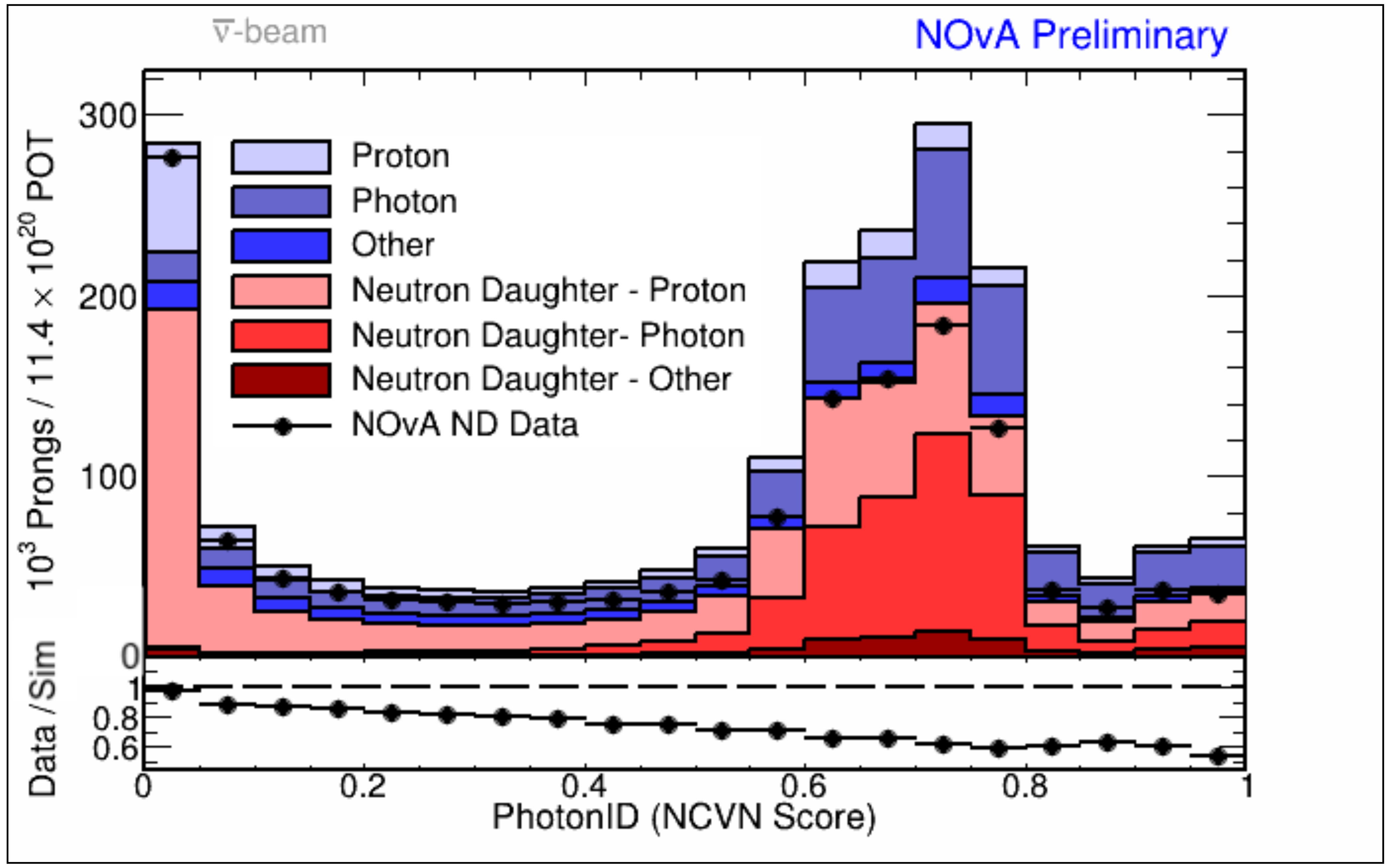




What's causing the discrepancy?

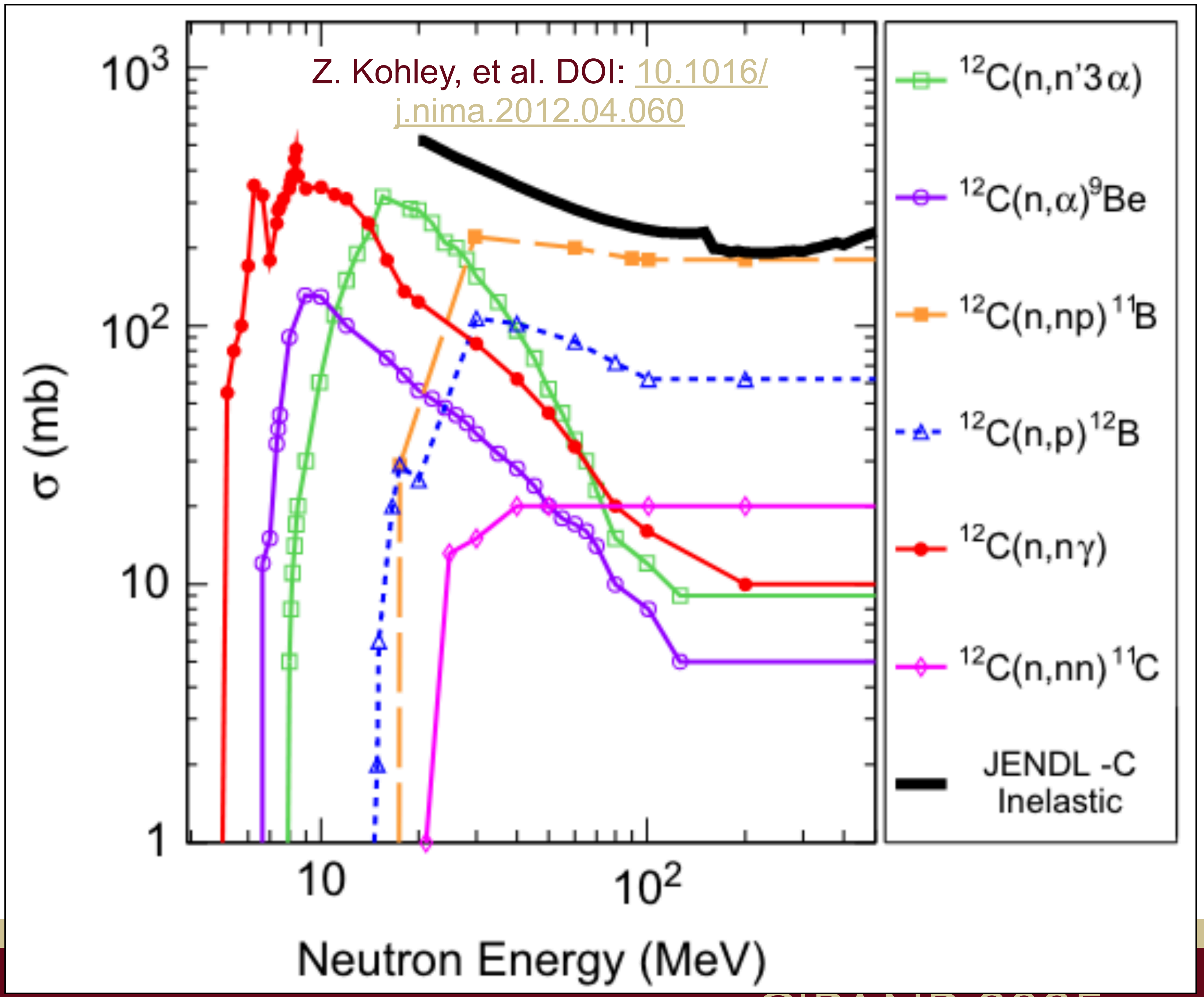
- De-excitation photons produced by neutron inelastic scattering (medium red) are concentrated at low energy where the simulation excess is the greatest
- We trained a neural network to identify neutron-daughter particle types
  - Over-simulation "follows" the photons





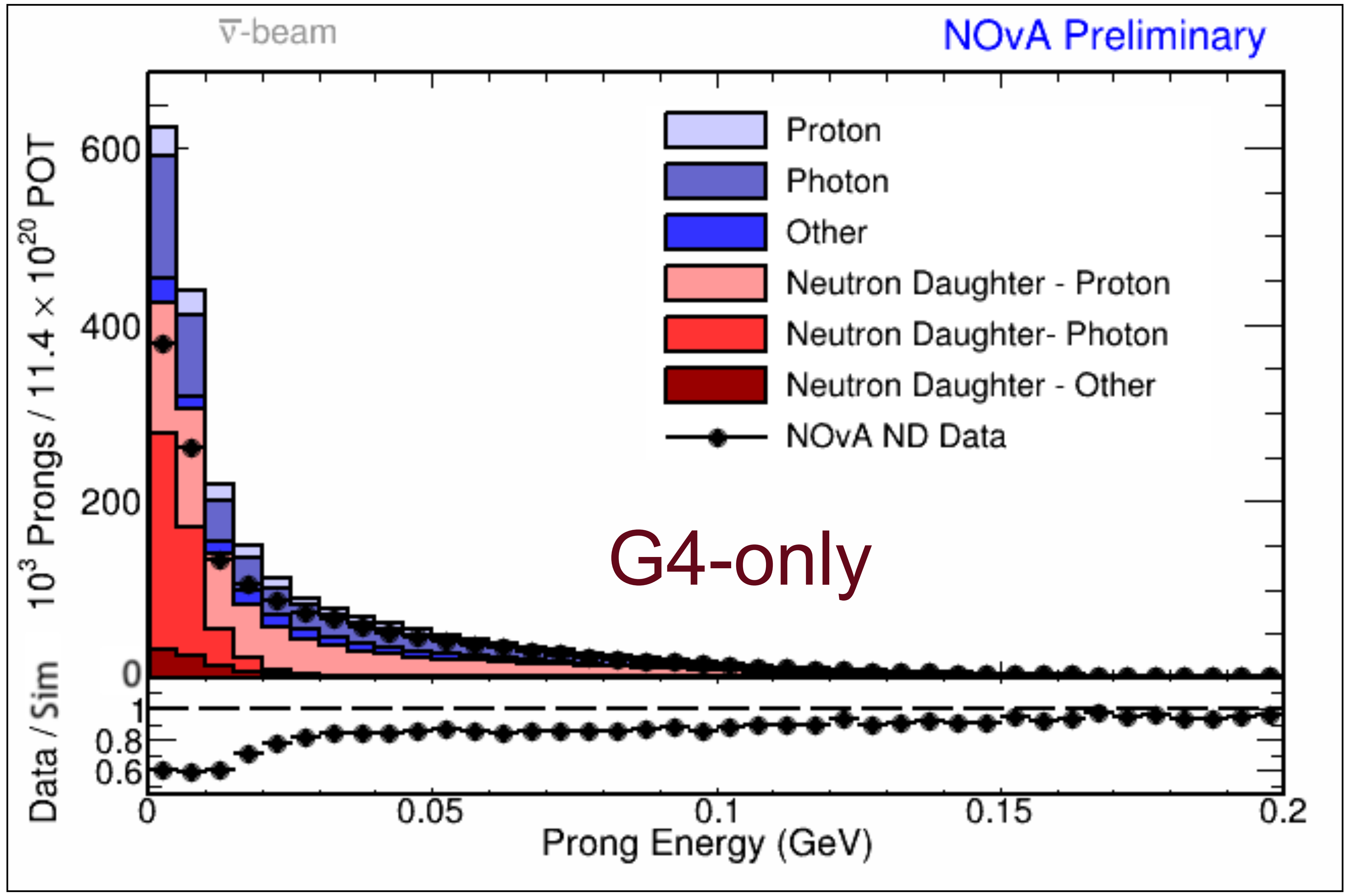
Alternative neutron inelastic model

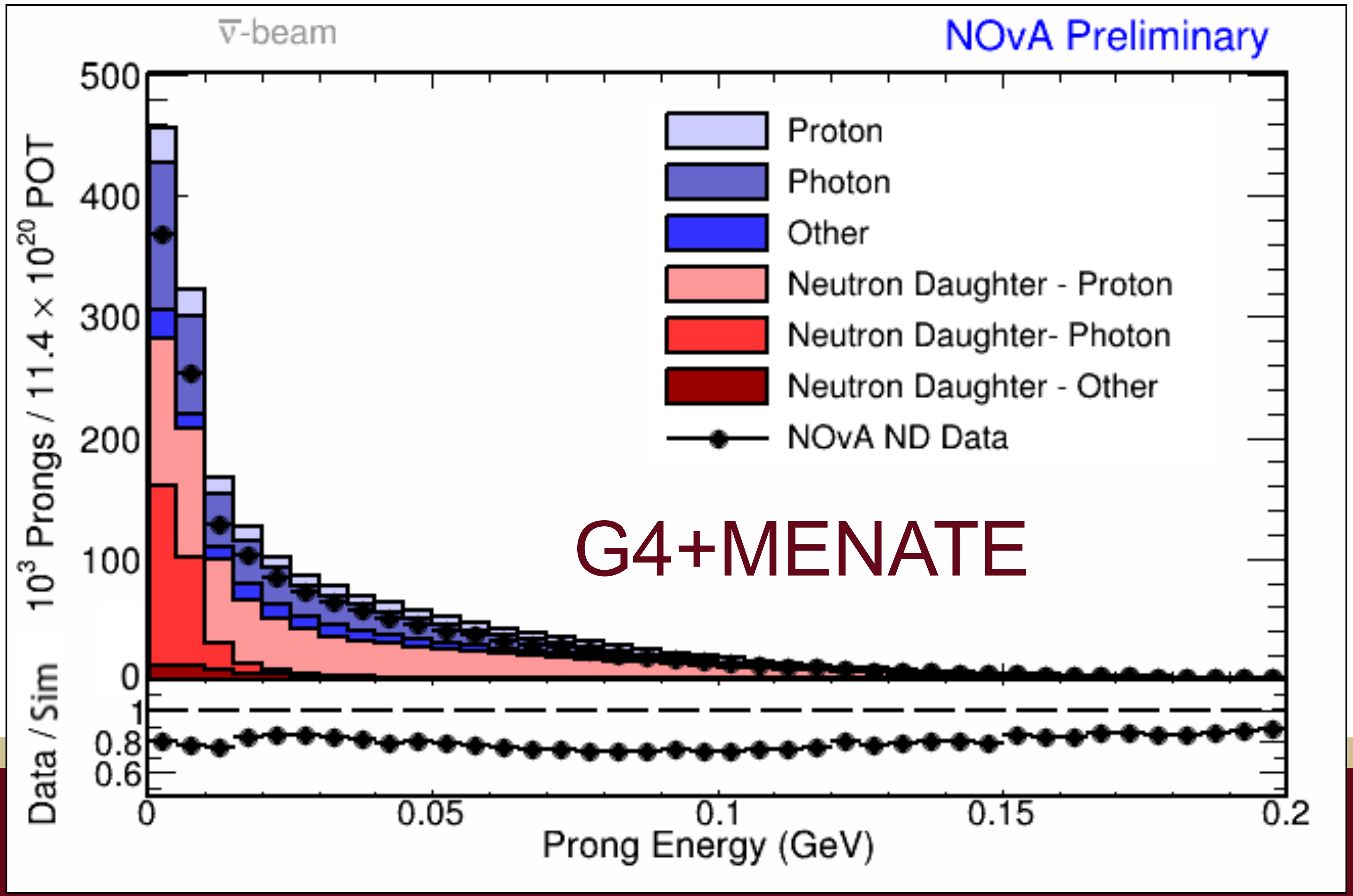
- De-excitation photons produced by Geant4:
  - The HP model: determines outgoing particles based on measurements (limited data)
  - Intranuclear cascade: theory-driven and statistically determines outgoing particles while using the overall cross-section
- "MENATE" extends the ethos of the HP model to higher energies
  - But only for neutron-on-carbon interactions (that's what we have data for)
  - Limits n+^{12}C to only 6 final states
  - Our implementation integrates directly with Geant4



Comparing to data

- MENATE reduces the over-simulation in the most populous bins
  - Photon production is significantly decreased
- It increases the over-simulation at higher energies
  - Proton production is slightly increased
- Overall, the data-simulation ratio is flatter, but there is still a significant over-simulation
  - Only addressing neutron-on-carbon; there are other targets and projectiles





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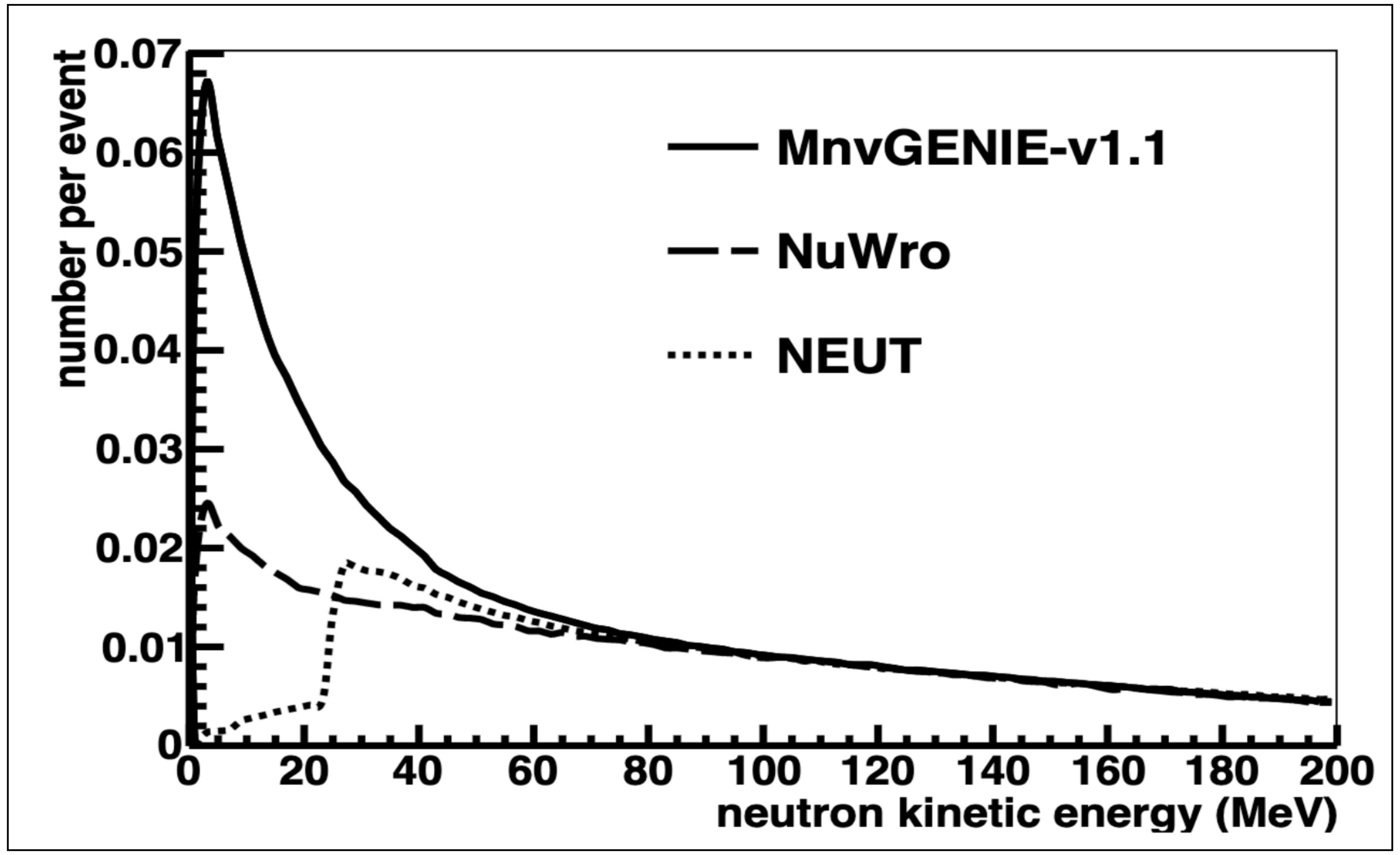
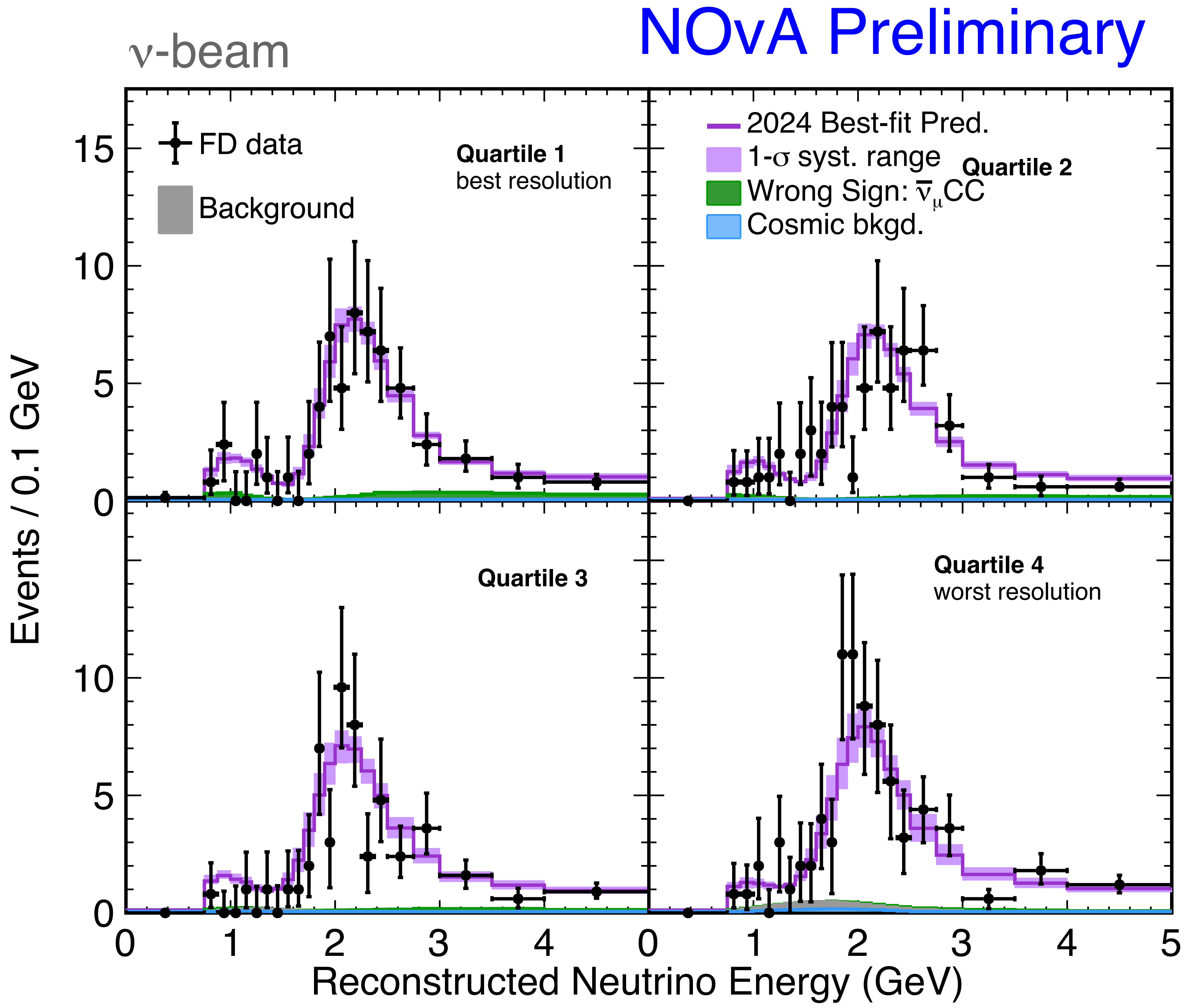
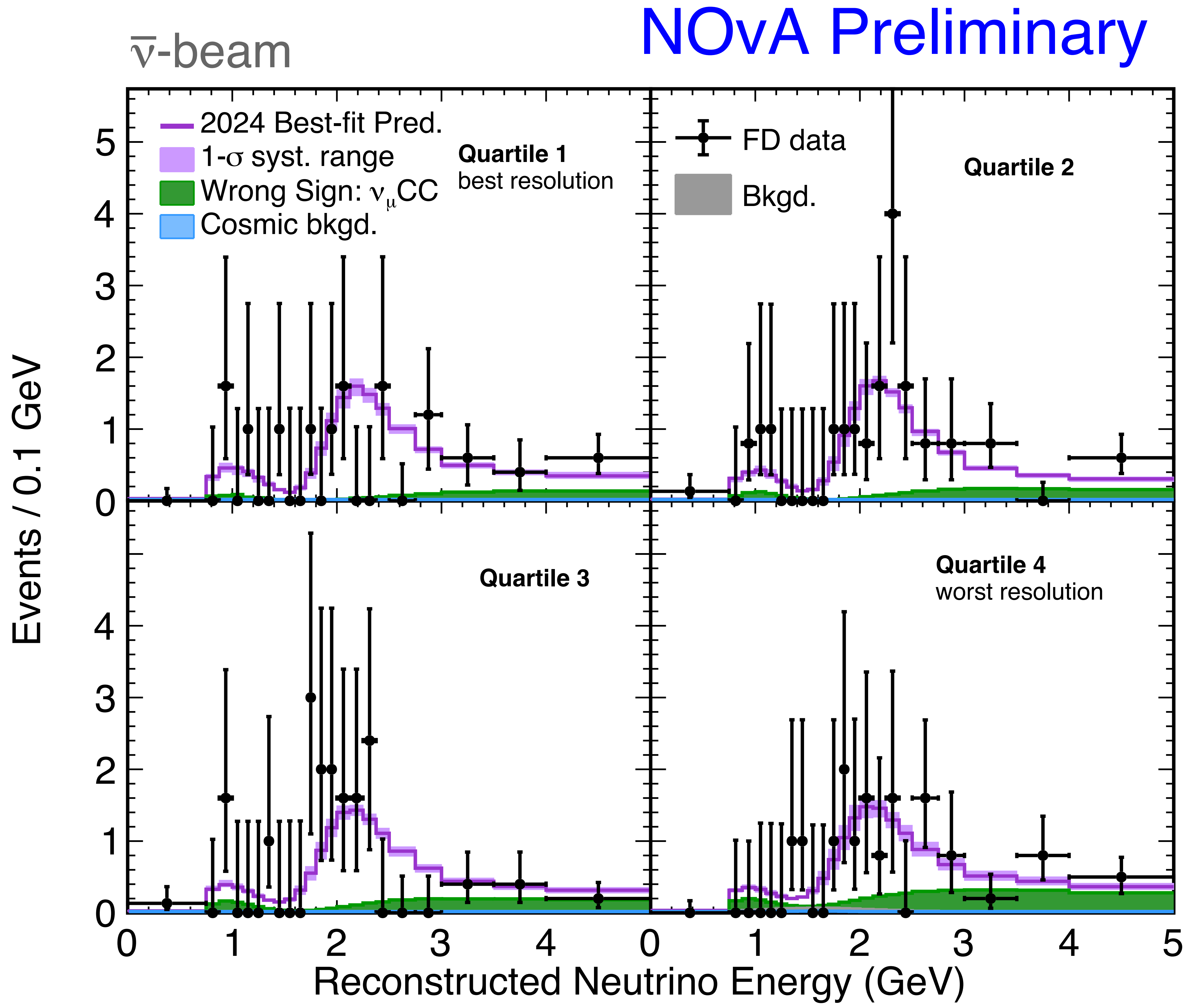
- Overall, the data-simulation ratio is flatter, but there is still a significant over-simulation
  - Only addressing neutron-on-carbon; there are other targets and projectiles
  - Large uncertainties on neutron production
    - This would produce a "normalization" discrepancy



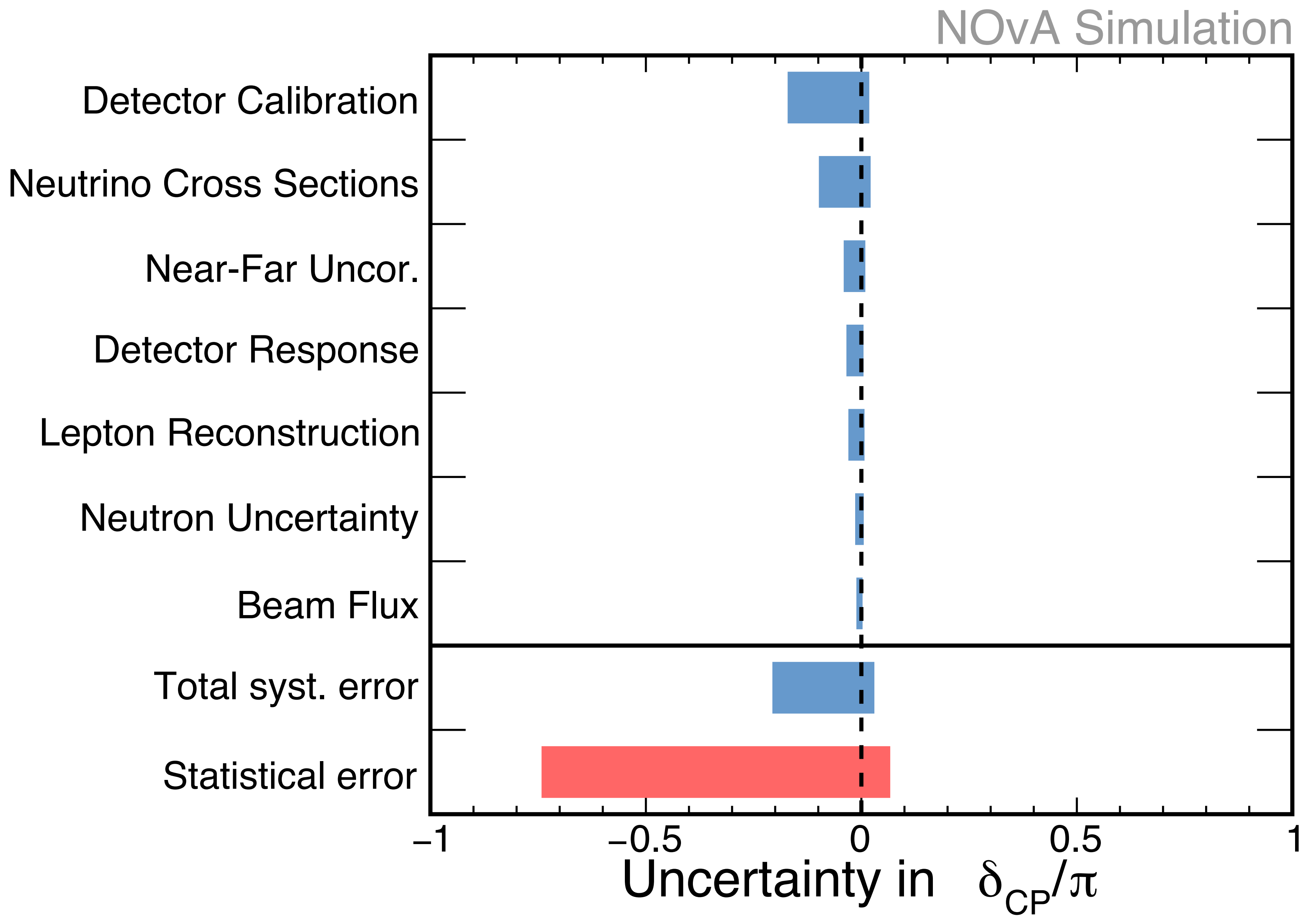
M. Elkins, et al. DOI: 10.1103/PhysRevD.100.052002

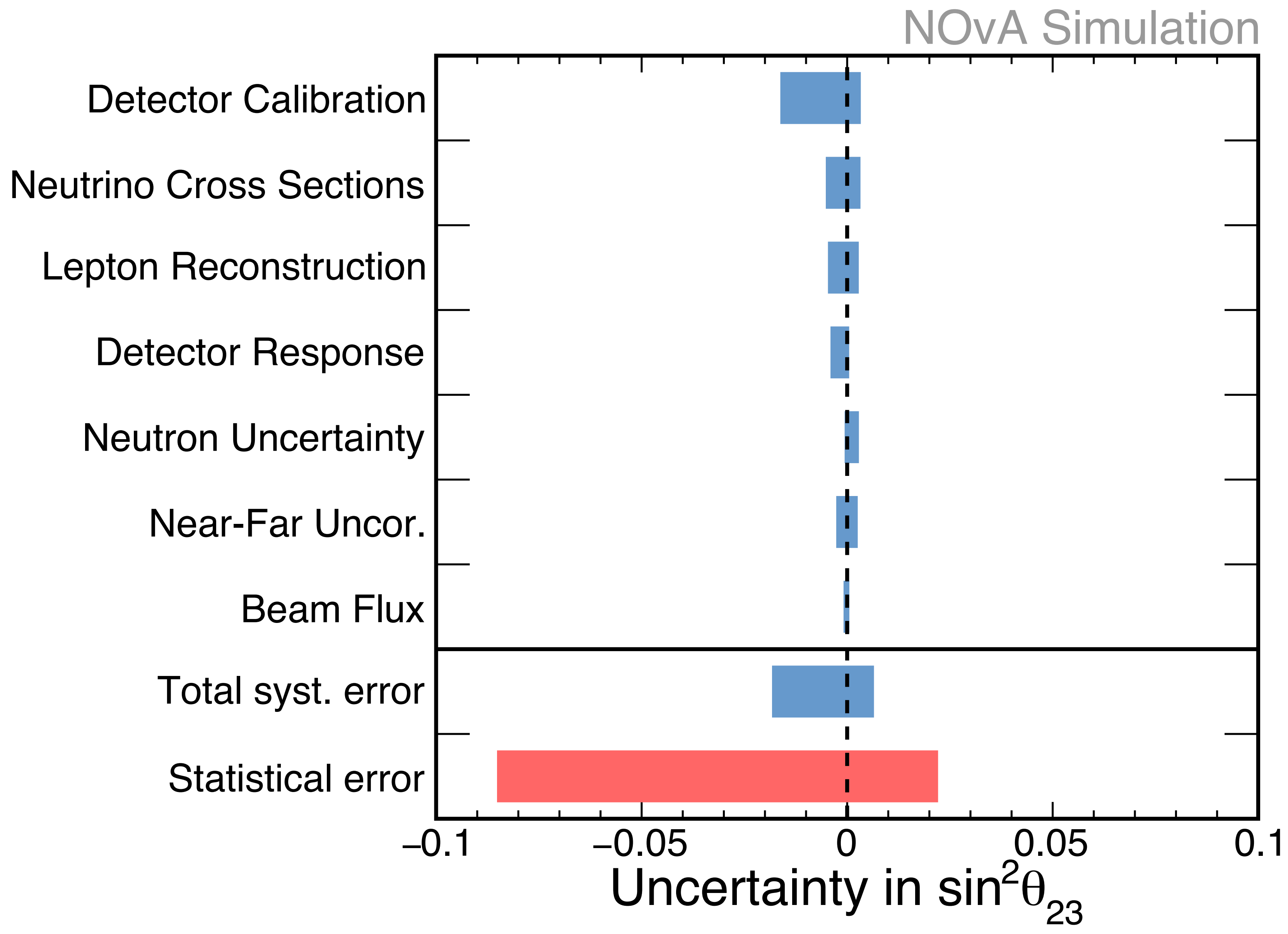
Numu Ehad Quants

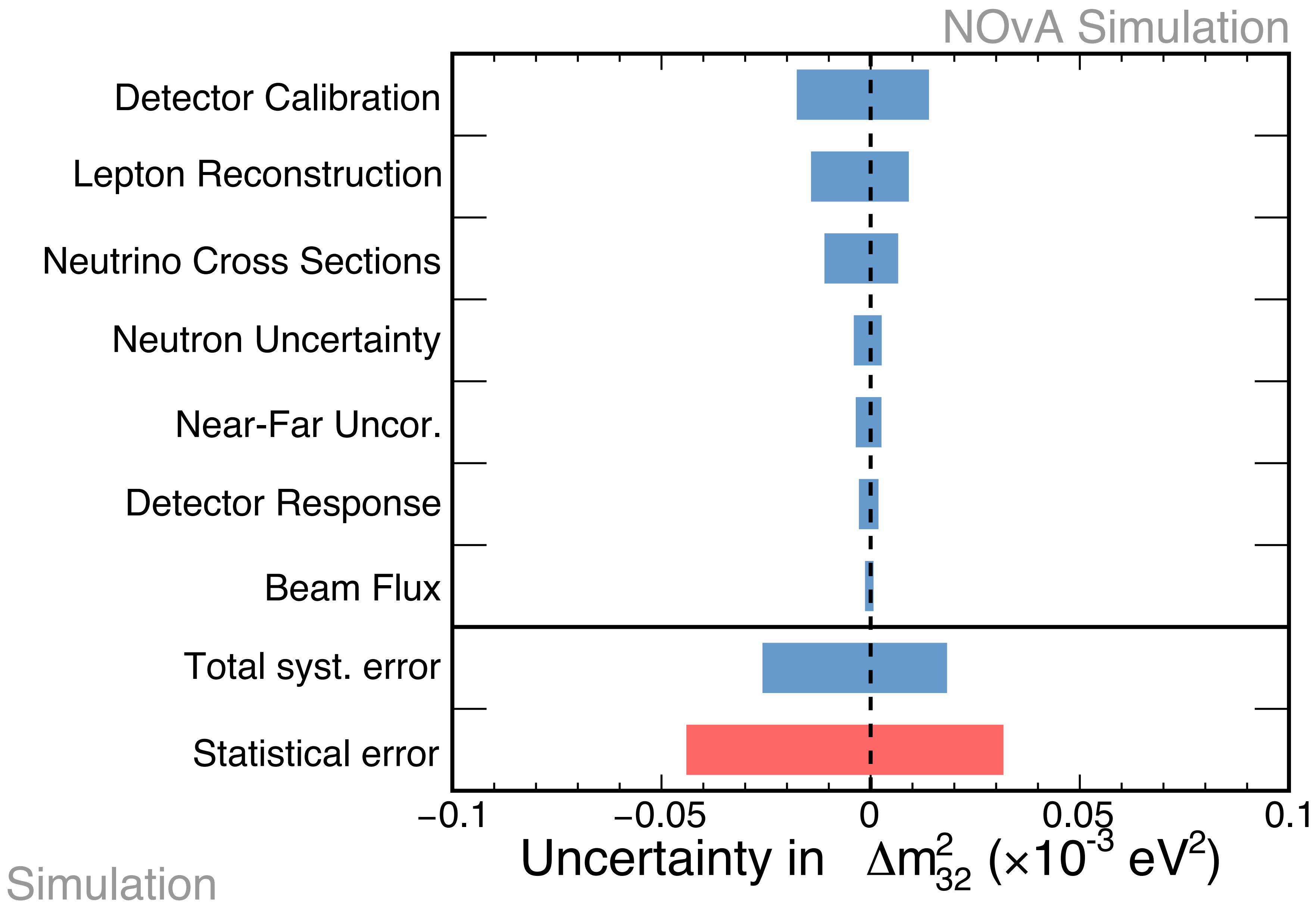




Freq. Uncertainties

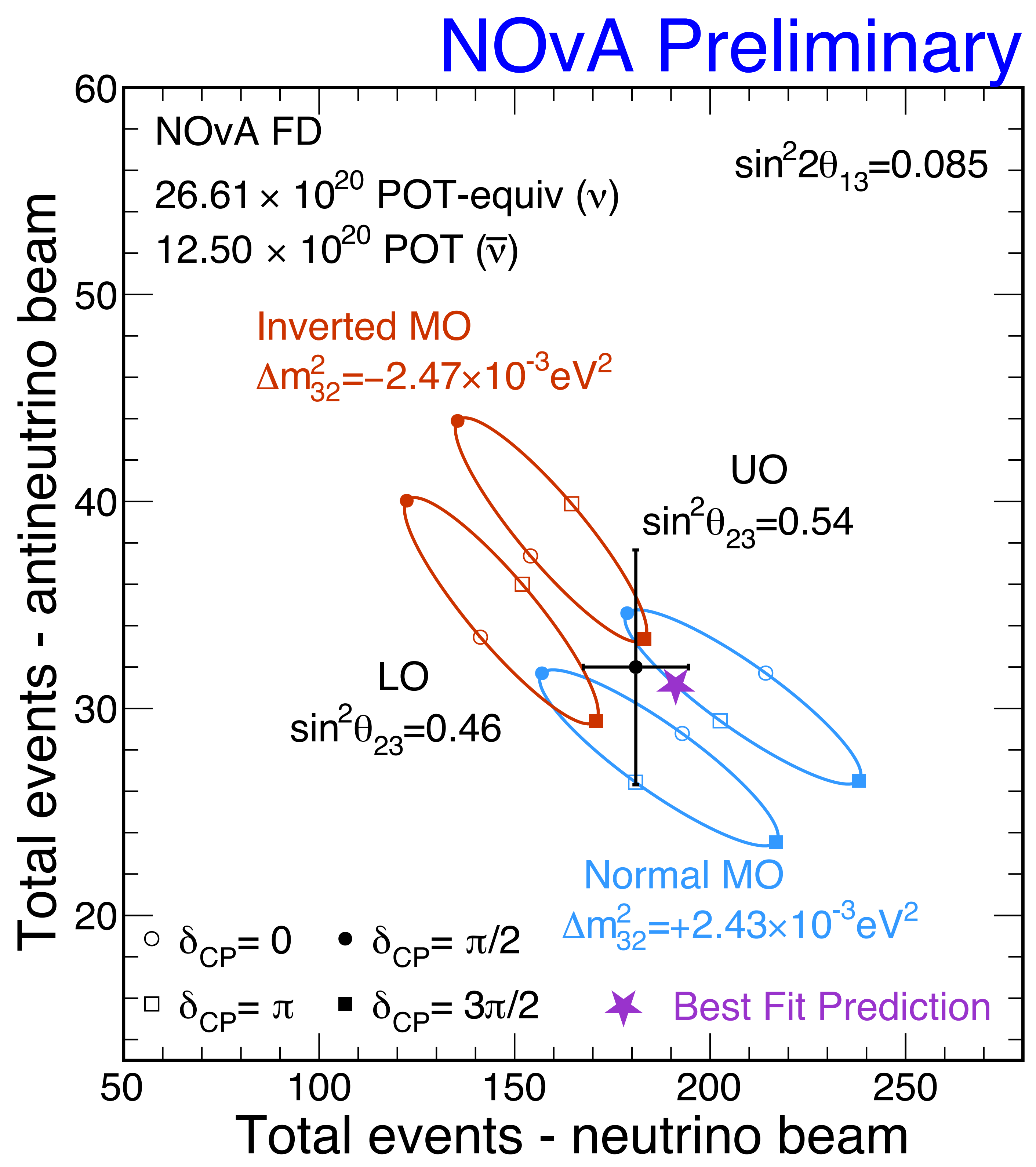




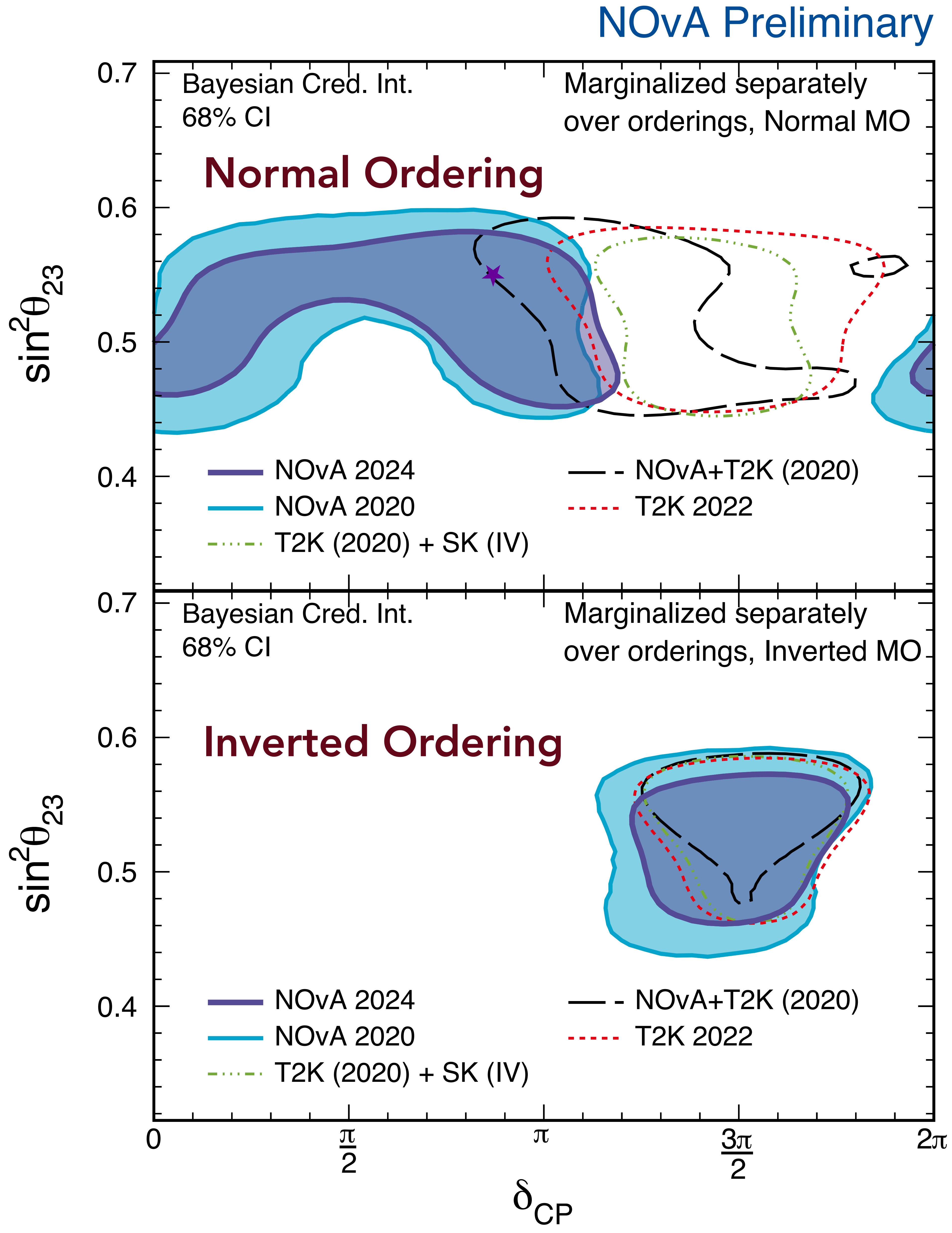


Bayesian results

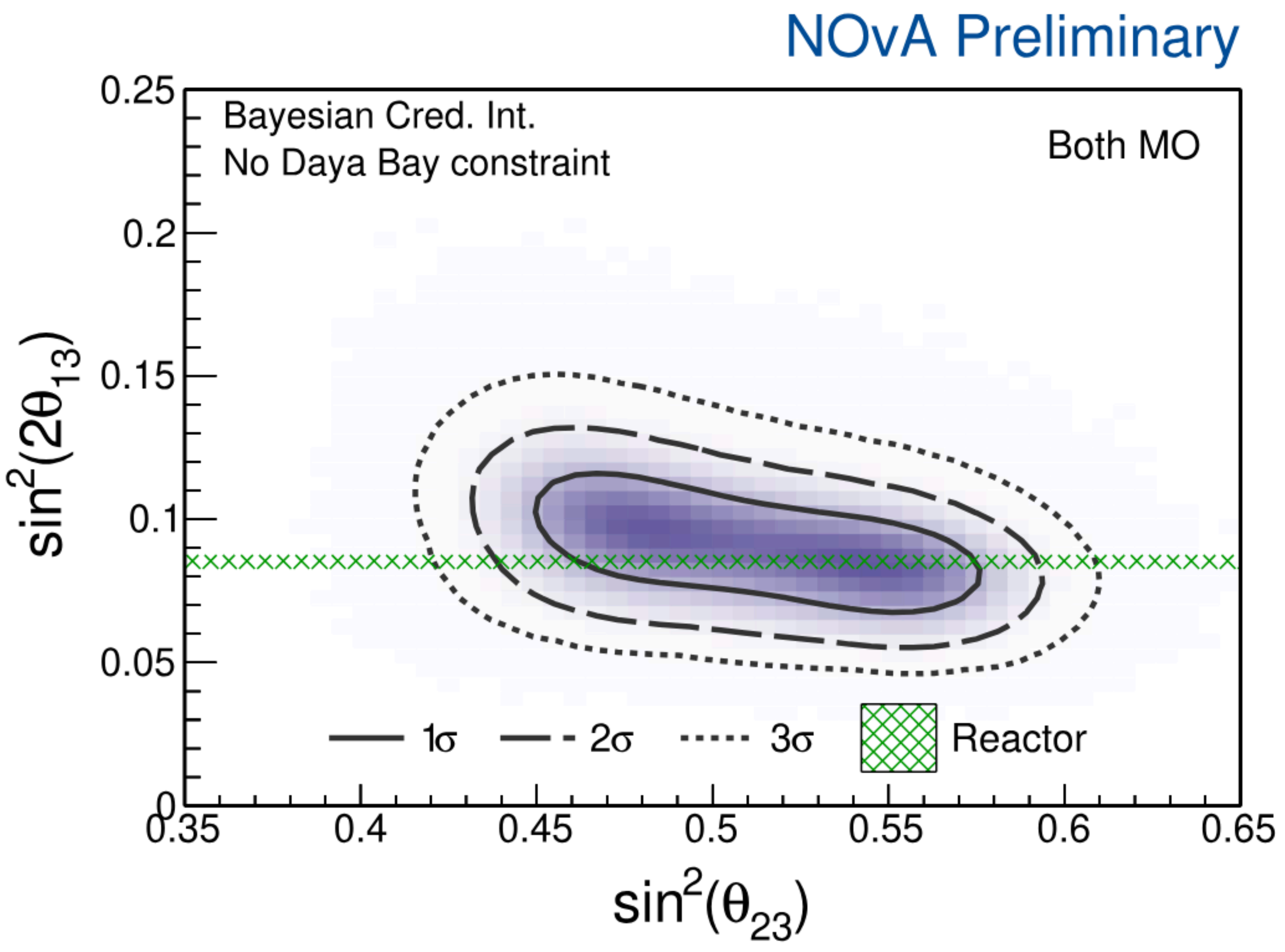
- Prefer CP conserving values of δ_{CP} in the normal mass ordering and CP violating values in the inverted

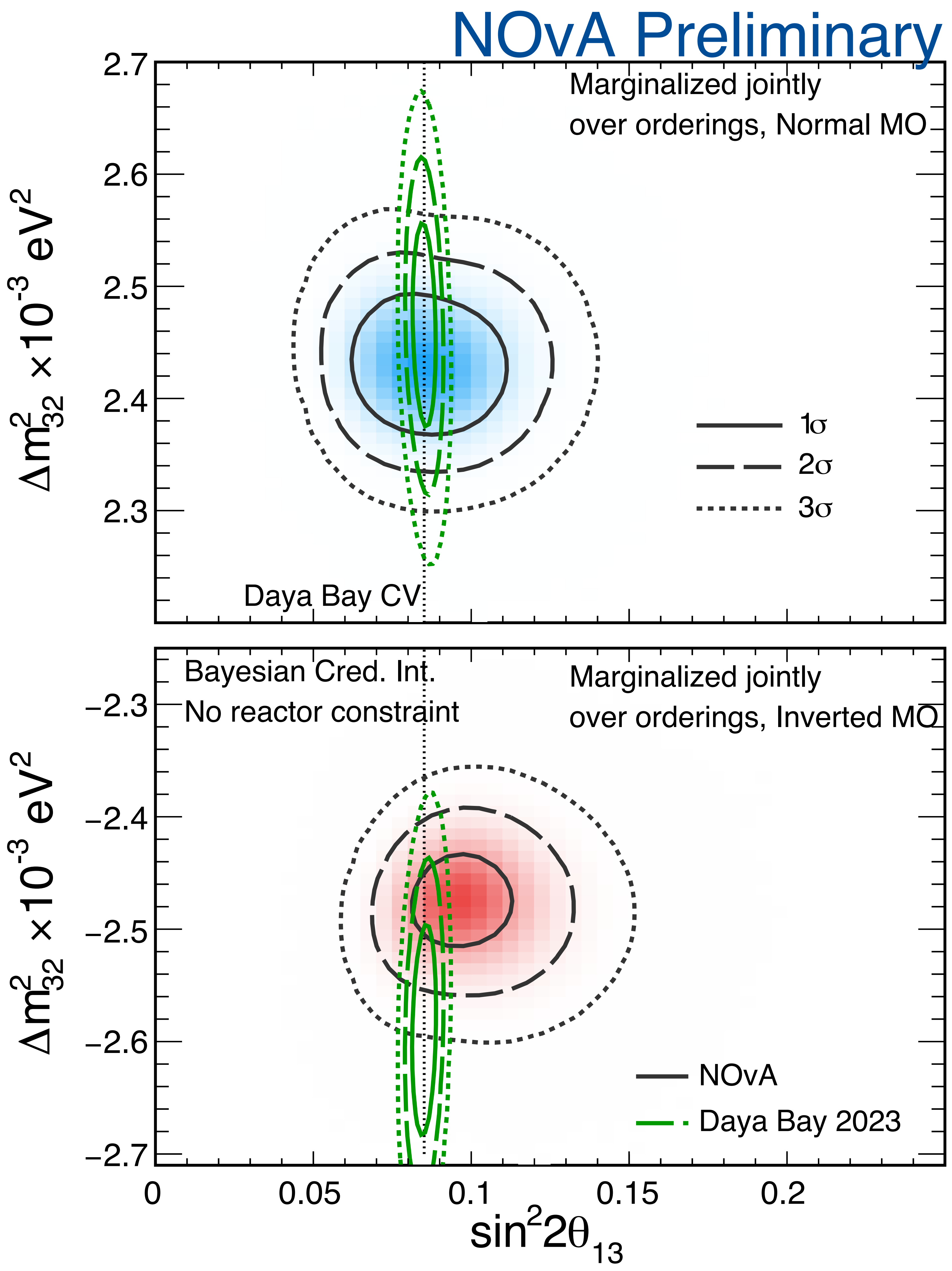


- Our data lie in the highly degenerate region
- Preference for normal mass ordering is enhanced by reactor constraints



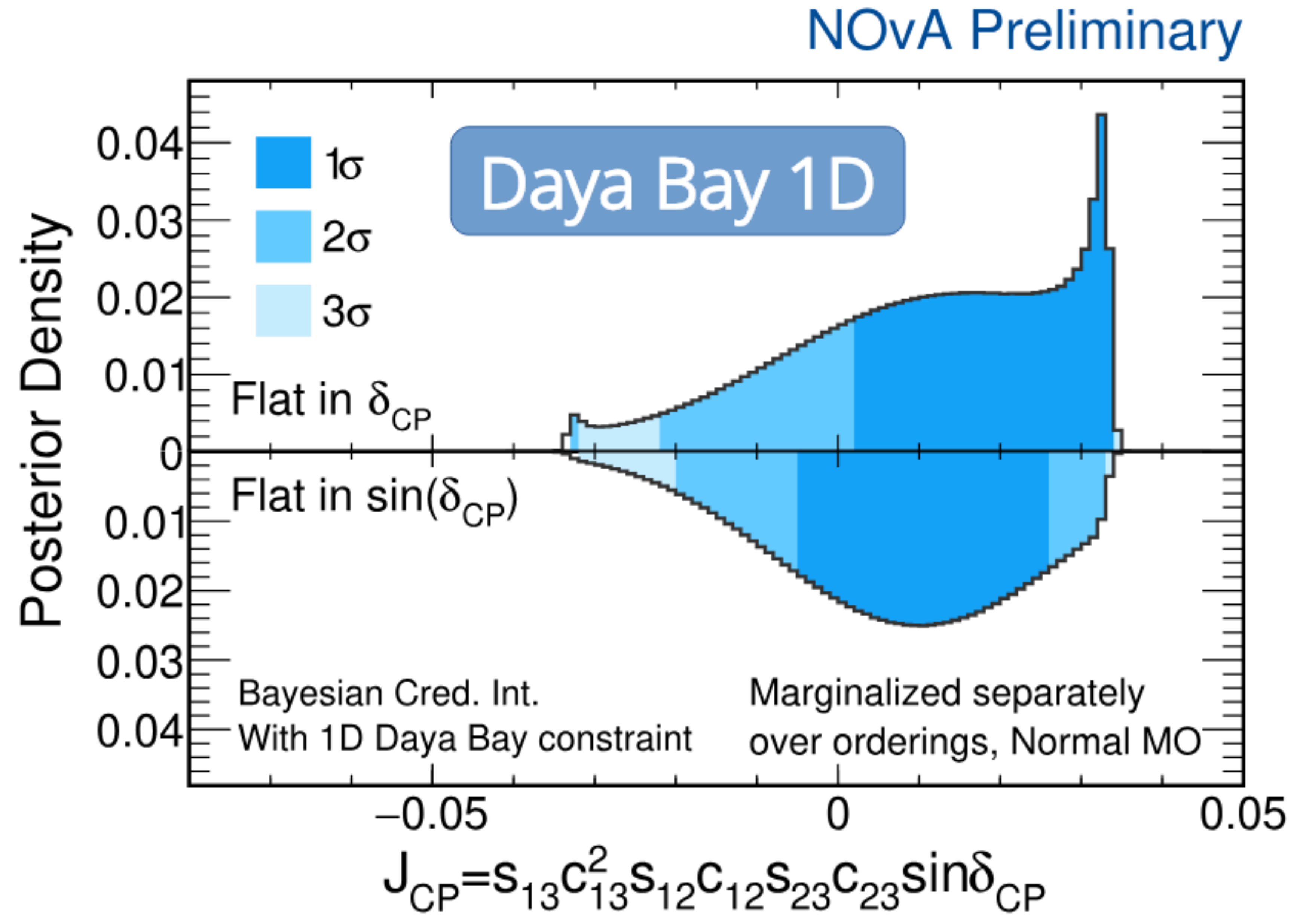
Daya Bay's constraint

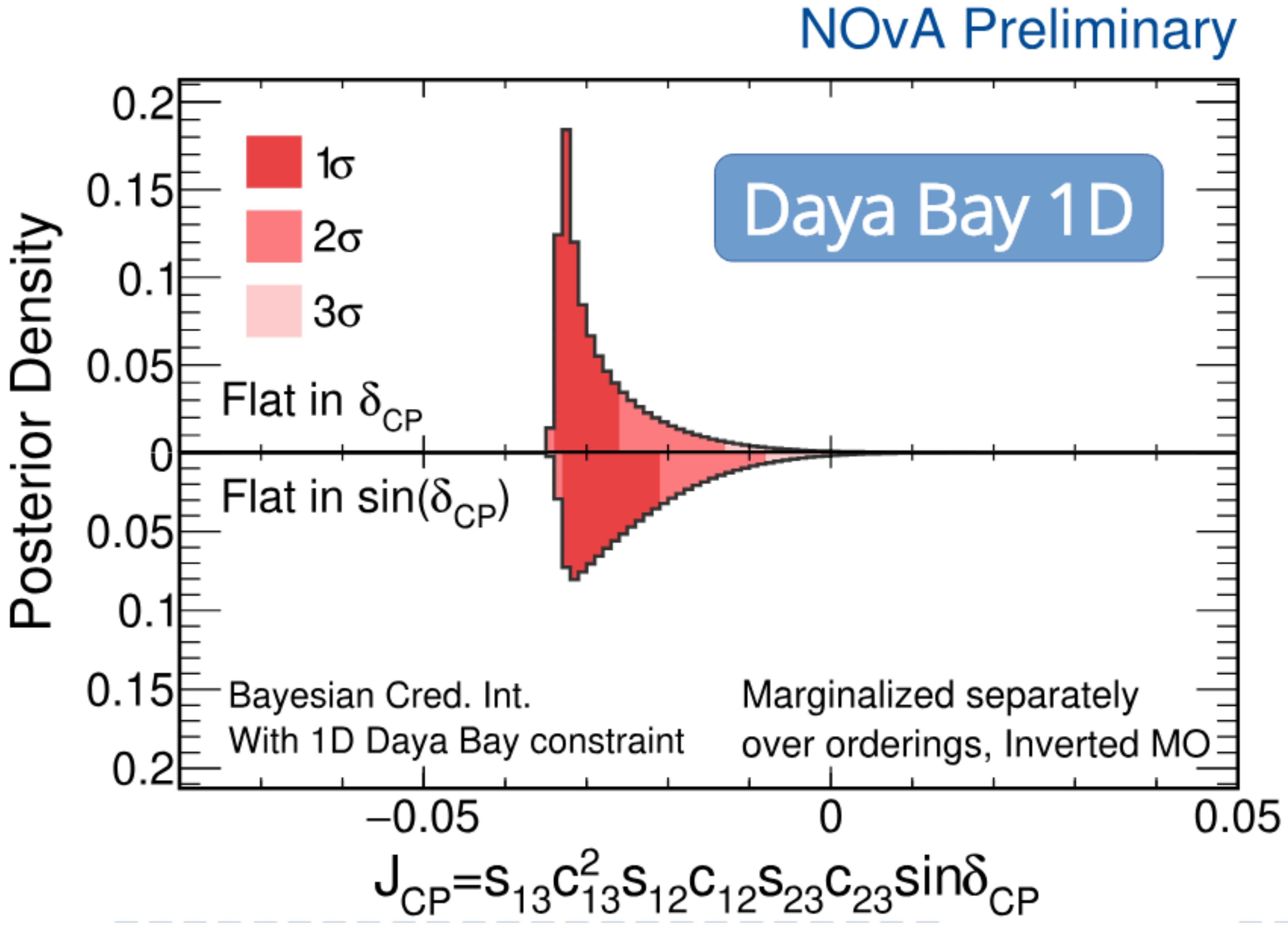




CP Violation

- The Jarlskog invariant is a parameterization-independent measure of CP violation
  - $J = 0 \rightarrow$ CP-conservation
  - $J \neq 0 \rightarrow$ CP-violation
- Choice of prior
  - Flat in $\sin\delta_{CP}$ provides data-only preference
  - Flat in δ_{CP} (theoretically motivated) is biased away from minimal-CP-violation
  - Doesn't impact interpretation of result



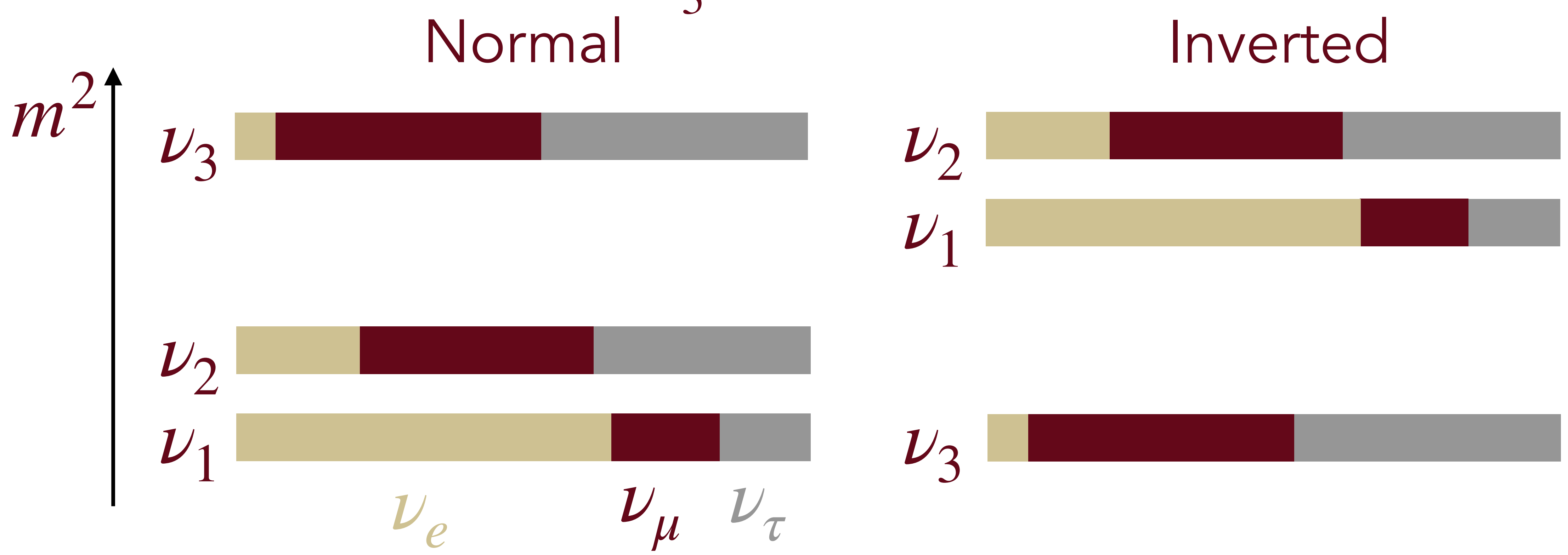


Neutrino oscillations in NOvA

3-flavor Oscillations

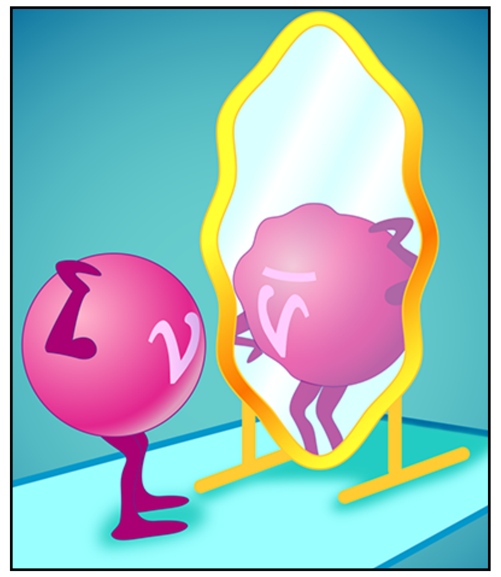
Mass Ordering

Is ν_3 the heaviest state?



CP Violation

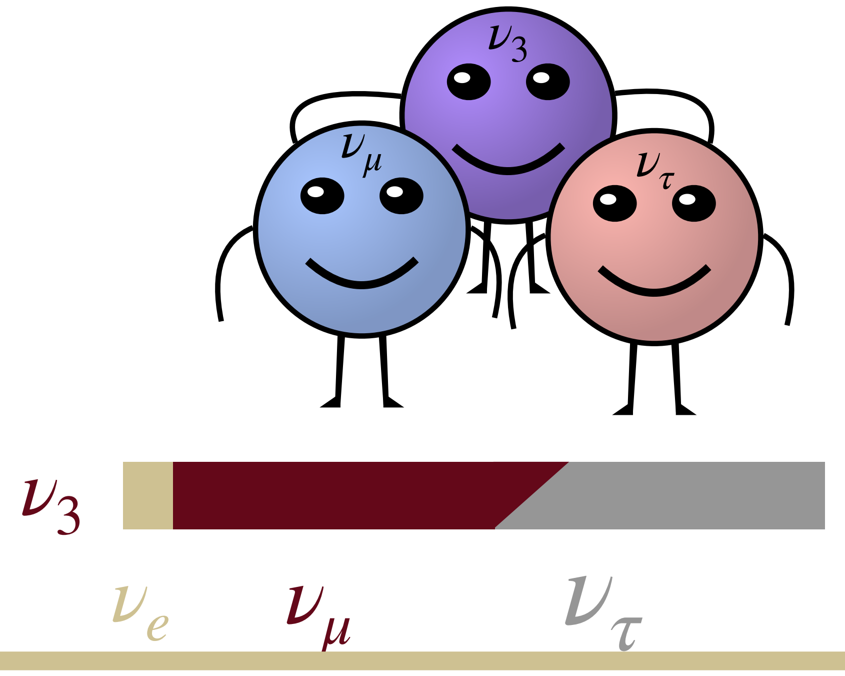
Is there a neutrino-antineutrino asymmetry?



Credit: APS/Carin Cain

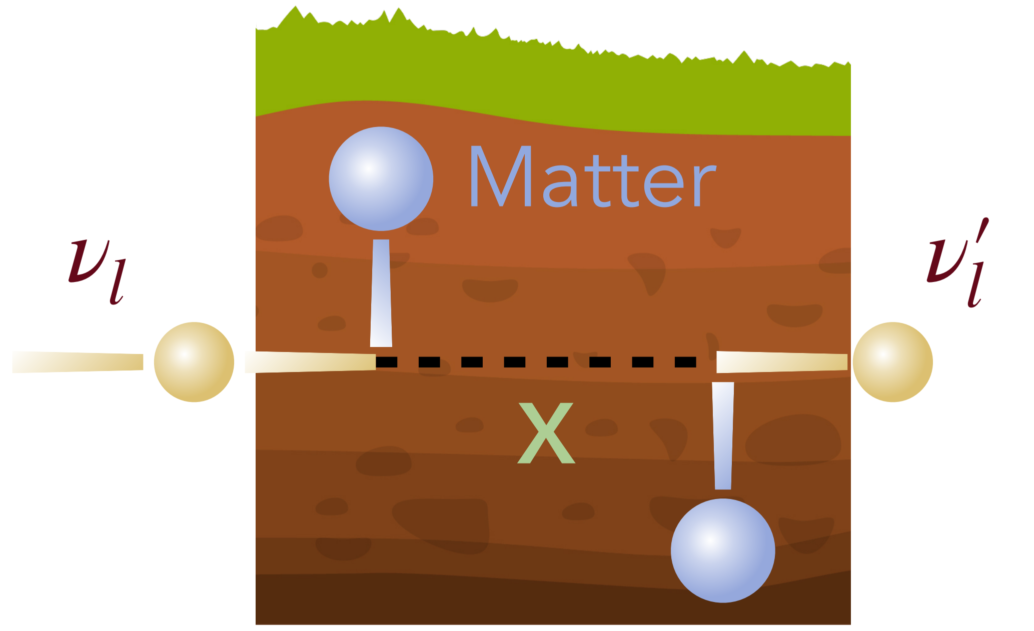
Maximal Mixing (θ_{23})

Do the ν_μ and ν_τ states couple equally to ν_3?

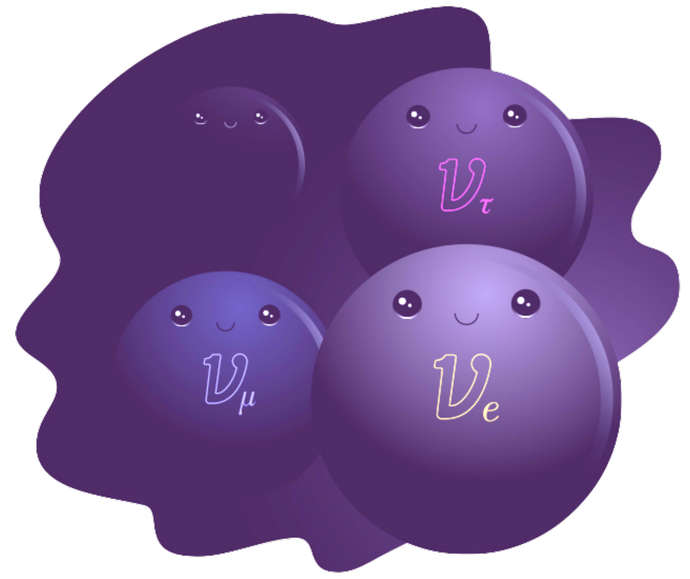


Beyond Standard Oscillations

Nonstandard interactions



Sterile neutrinos



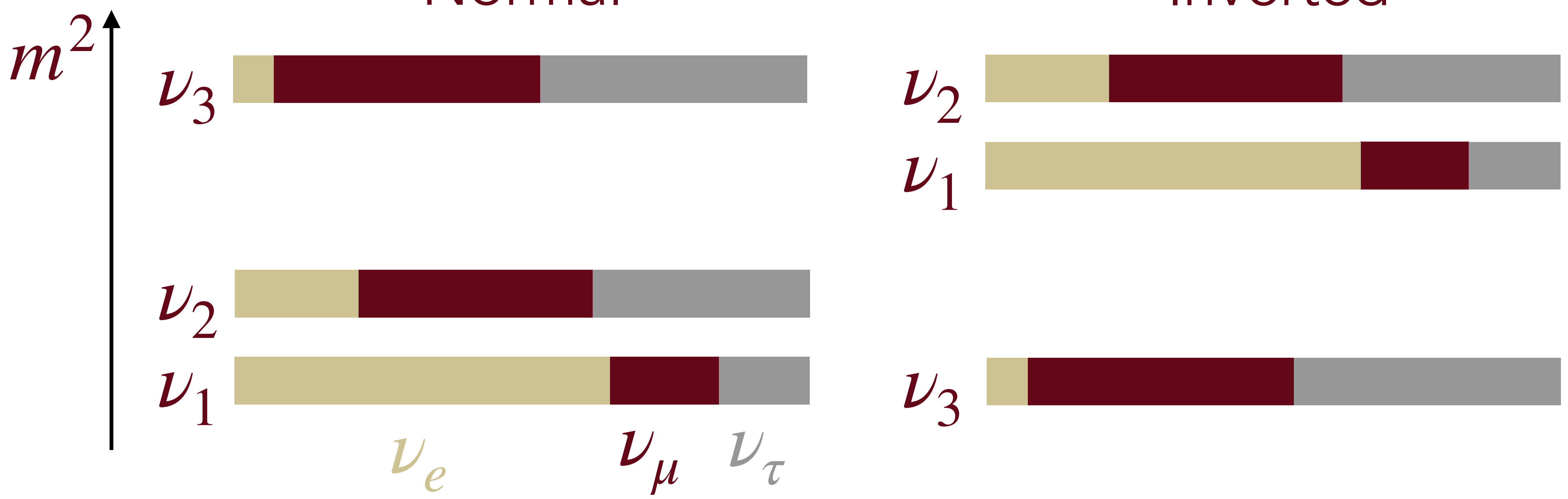
Credit: Symmetry magazine, Illustration by Sandbox Studio, Chicago with Ana Kova

3-Flavor Oscillations

Mass Ordering

Is ν_3 the heaviest state?

Normal Inverted



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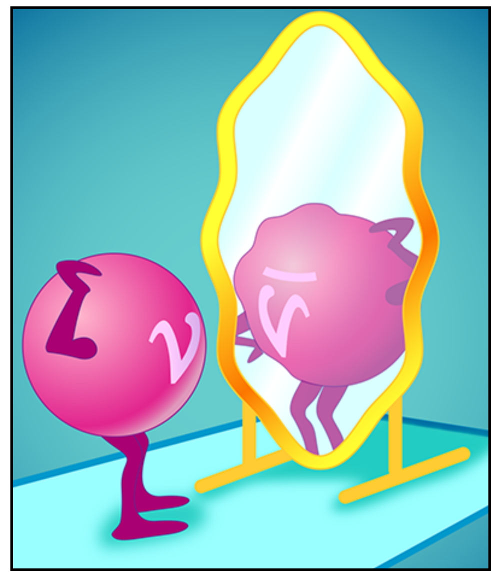

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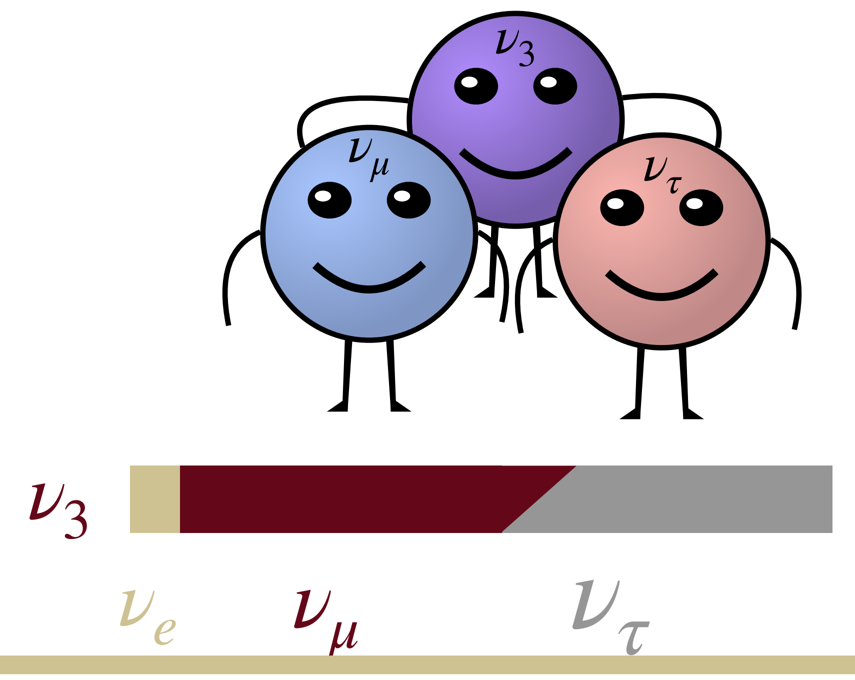

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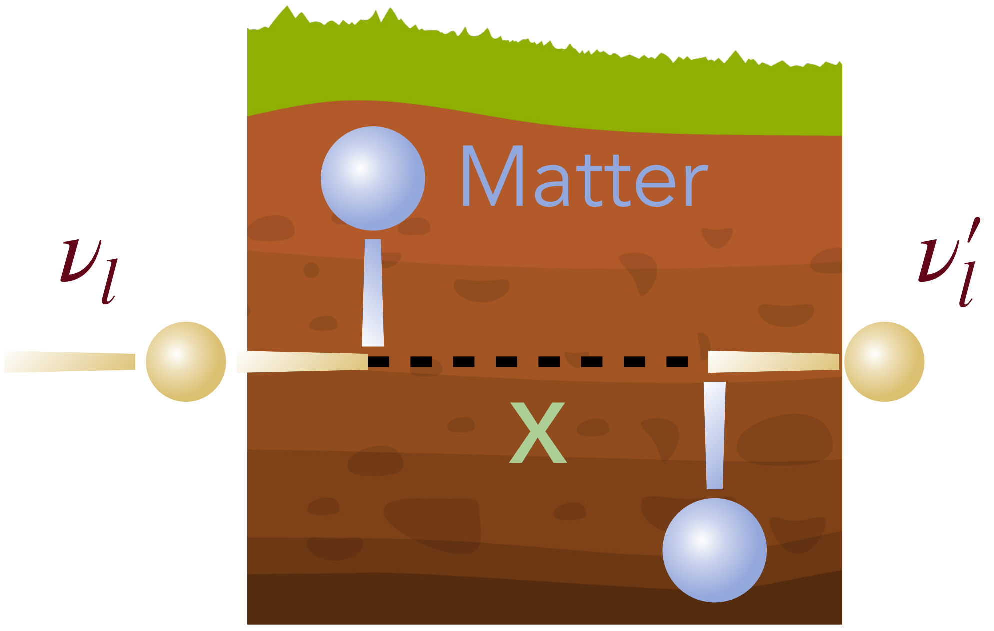
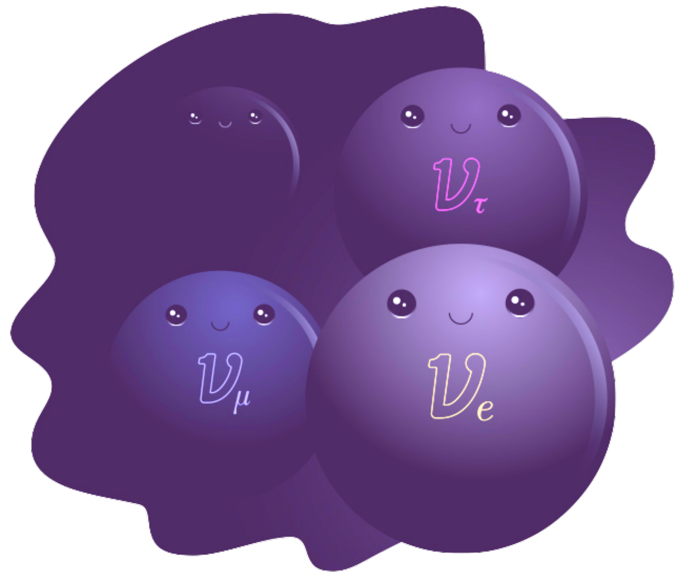


$$\mathcal{H} = U\mathcal{H}_0U^\dagger + \sqrt{2}G_F n_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Sterile neutrinos



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$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

3+1 model